DOCUMENT RESUME

ED 111 662 SE 019 617

AUTHOR	Fowler, John W.
TITLE	Energy-Environment Source Book. Volume 1: Energy, Society, and the Environment. Volume 2: Energy, Its Extraction, Conversion and Use.
INSTITUTION	National Science Teachers Association, Washington, D.C.
SPONS AGENCY	Office of Education (DHEW), Washington, D.C. Office of Environmental Education.
BUREAU NO	BR-0-047FPA
PUB DATE	75
CONTRACT	OEC-0-74-8736
NOTE	270p.; For related documents, see SE 019 618 and 619
AVAILABLE FROM	National Science Teachers Association, 1742 Connecticut Avenue, N. W., Washington, D. C. 20009 (Stock Number 471-14692, $4.00 prepaid)
EDRS PRICE	MF-$0.76 Plus Postage. HC Not Available from EDRS.
DESCRIPTORS	Conservation (Environment); Elementary Education; *Elementary School Science; *Energy; Environmental Education; Instructional Aids; *Instructional Materials; *Natural Resources; Science Education; Secondary Education; *Secondary School Science
IDENTIFIERS	National Science Teachers Association; NSTA

ABSTRACT

This source book, one part of a three-part NSTA series on energy-environment, is written for teachers who wish to incorporate material on the complex subject of energy into their teaching. This work is divided into two volumes, each with numerous tables and figures, along with appendices containing a glossary, mathematics primer, heat engine descriptions, and nuclear energy discussion. Volume 1 (Energy, Society, and the Environment) deals with energy and its relationship with conservation, the environment, the economy, and strategies for energy conservation. In Volume 2 (Energy, Its Extraction, Conversion, and Use), topics discussed include the rate of energy consumption, future sources of energy, and the increased cost of energy. (Author/CP)

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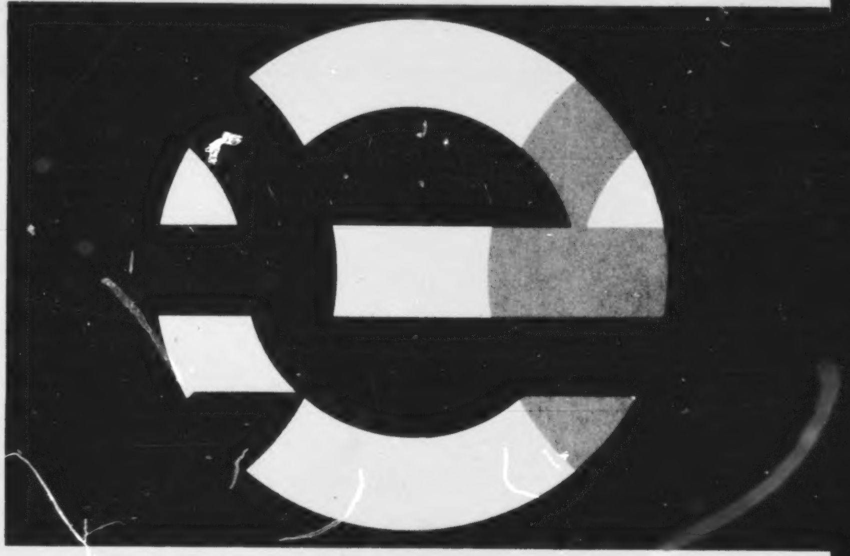

Volume 1	Volume 2
Energy, Society, And the Environment	**Energy, Its Extraction, Conversion, And Use**

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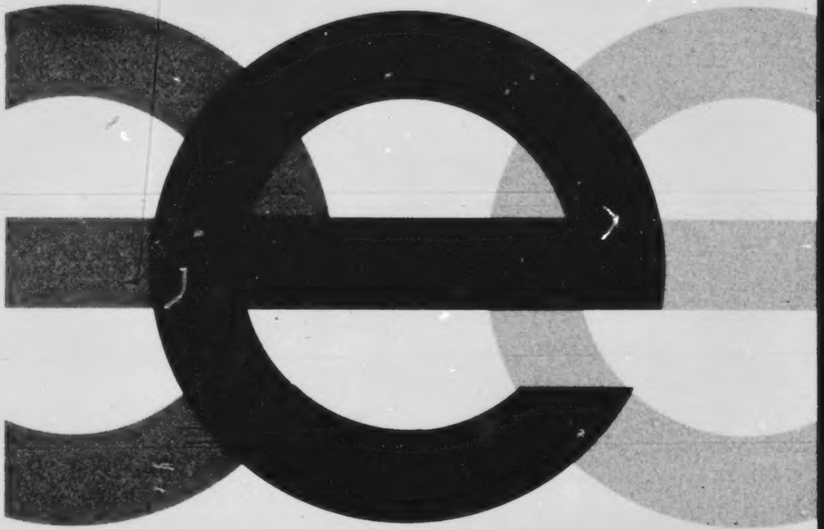

Volume 1
**Energy,
Society,
And the
Environment**

Volume 2
**Energy,
Its Extraction,
Conversion,
And Use**

John W. Fowler

NSTA

National
Science Teachers
Association

1742 Connecticut Avenue, N.W.
Washington, D.C. 20009

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ENERGY-ENVIRONMENT SOURCE BOOK

John M. Fowler

A product of the
NSTA Energy-Environment Materials Project
John M. Fowler, Director

The development of these materials was supported by the Office of Environmental Education under the Environmental Education Act of 1970 (P.L. 93-278).

Contract #OEC-0-74-8736
Project R0047FPA
Division of Technology and Environmental
Education, U.S. Office of Education

Publication and distribution was supported, in part, by a contract from the Office of Conservation Education of the Federal Energy Administration.

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Stock No. 471-14692 Price: $4.00

To my children, Lee, Lynn, Kay, Kurt, Leslie, Ada, and Marian, who will need energy for their future.

JMF

PREFACE

This Source Book is written for teachers who wish to incorporate material on the complex subject of energy into their teaching. I have tried to condense the voluminous information on energy and on its interaction with society and the environment and to present it in an objective and readable style.

I was greatly assisted in this endeavor by the project staff and in particular by Stephen Smith and James V. DeRose who read and commented on most of the manuscript.

The Advisory Committee, whose members are listed in the Foreword, was helpful through all phases of this project. Richard Scheetz, William Burton, Betsy Kraft, Charles Pelzer, and Alice Tetelman of the Advisory Committee gave assistance well beyond the call of duty.

The Source Book also profited from the attention of the several teacher-reviewers listed in Appendix 7.

Nancy Smith edited much of Volume II and compiled the Glossary. Stephen Smith wrote the first drafts of the Technical Appendices. Elizabeth Weiner performed the difficult task of editing before final publication.

The typing was done by Dianne Schroeder and Brenda Gainor. Carol Lee Bloom, the Executive Secretary of the project, also drew most of the Source Book figures.

I wish also to extend my personal gratitude and that of the project staff to Robert L. Silber, Executive Director, and the people of the National Science Teachers Association for their hospitality and support, and to Walter Bogan, Director of the Division of Technology and Environmental Education, U.S. Office of Education, whose support and encouragement made the project possible and enjoyable.

JMF

January 1975

FOREWORD

The members of the Advisory Committee of the NSTA Energy-Environment Materials Project are united in their belief in the importance of this project. The complex energy-environment subject contains in it some of the most crucial issues of our time. It is a subject that deserves a place in school curricula. We hope and believe that these materials will be of great assistance to teachers and students who wish to bring these concepts and issues into their courses.

The Advisory Committee was assembled to gain the diverse perspectives of a variety of interests and points of view. We have read these materials, discussed them at several meetings and with individual staff members, and have made suggestions and comments. Many of these have been incorporated in the materials. With the diverse points of view represented, complete unanimity cannot be expected, but the Committee is satisfied that the materials represent a balanced presentation. Dr. John Fowler, his staff, and the National Science Teachers Association should be commended for this fine effort. The Division of Technology and Environmental Education of the U.S. Office of Education should be likewise commended for financial support of this project.

Finally, it should be noted that members of the Advisory Committee speak as individuals and not in an official capacity for the organizations with which they are associated.

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---

[1] Represented by Burrell Wood, October 29 and December 17

[2] Represented by Paul Loris, July 31

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INTRODUCTION
A Review and A Preview

A Review and a Preview

The "Shootout" at Four Corners

In 1950, Los Angeles was riding the bow wave of American growth. Population, metropolitan area, expressway mileage, economic importance were all increasing. Its consumption of energy, especially electricity, also was growing rapidly. The number of automobiles was increasing and, not coincidentally, Los Angeles was in the front rank in another area — air pollution.

The growth in electric energy consumption, the demand doubling every nine years, demanded the continual addition of new generating plants. Here, however, the city's eager consumption of electricity, to cool in summer and warm in winter, and to turn the motors of industry, collided with hard meteorological and geographical facts. Although California has ample oil and natural gas resources, the tendency of air pollutants to hang long in the air above the city makes its citizens reluctant to burn even these relatively clean fuels in their power plants. A decade or so before the rest of the country, Los Angeles was hung on the horns of the energy-environment dilemma.

Help was not long in coming. Beyond the mountains and deserts to the east, in the area surrounding a place called Four Corners (the point where New Mexico, Colorado, Utah, and Arizona join), were enormous resources of coal. This coal was not only a potential source of energy, but it underlay a relatively uninhabited, arid land with no air pollution problems. The Arizona Public Service Company was building a huge coal-fired generating plant there and plans were made to transmit the electrical power by high-voltage transmission lines to Los Angeles and other Southwestern areas.

The Four Corners Plant, near Farmington, New Mexico, began operation in the mid-1960s and by that time plans were on the drawing boards (in some cases construction had begun) for five other huge plants. By 1969, the air pollution from the Four Corners Plant, the realization of the massive social and environmental changes that were taking place, and the complaints of many of the local citizens, attracted national attention. Particularly sensitive, and well-suited to dramatic defense, was the proposed location of one of the largest mines on Indian land, the "Black Mesa," the ancestral home of the Hopi and Navajo Indians that is considered sacred by many of them. The Sierra Club and other environmental organizations rallied to opposition, the Governor of New Mexico proposed a moratorium on coal plants in the region, and the battle was on.

Controversy over the plants in the Four Corners area was at its height several years ago. It's now ancient history. We review it in this introduction, however, because it has in it many of the components of the enlarging energy-environment dilemma that we now face as a country, and because it illustrates the mixture of fact and emotion, reason and irrationality, that is erupting on a national scale. We can best describe this mix by quoting from the Senate Hearings[1] that were held in the spring and summer of 1971 on the problems and potential of these power plants. These quotations tell their own story:

From an advertisement in The New York Times by the "Black Mesa Defense Fund":

"... LIKE RIPPING APART ST. PETER'S, IN ORDER TO SELL THE MARBLE.

"So that the world can have still more of Los Angeles, Las Vegas, and Phoenix, six gigantic coal-burning power plants and three huge strip-mines are underway at and around Black Mesa, Arizona. When operative, the complex will spread more deadly smog and soot than currently put out in New York and Los Angeles combined, across what is now 100,000 square miles of open country; the last pure air in America.

"Affected by the smog will be six national parks, 28 national monuments, the Lake Mead and Lake Powell recreation areas, and Grand Canyon; the places people escape to are being sacrificed to make more of what they escape from. Also being sacrificed on behalf of urban growth: the sacred religious shrines of the Hopi and Navajo Indians, who had thought that it couldn't happen again."[2]

From the Federal Power Commission:

"Demands for more and more electricity to meet industrial needs for production of goods and services, society's desires for greater comforts and conveniences, and commercial uses associated with the high standard of living in the United States have resulted in an approximate doubling of electric loads in each decade for a number of years. Forecasts indicate that this trend is likely to continue throughout the remainder of the century.

"The Federal Power Commission's West Regional Advisory Committee for the National Power Survey has confirmed that the western portion of the United States will likely follow the national trend and that electric generation in that region will in 1980 be about twice and in 1990 about four times that in 1970. In the past, much of the electricity requirement of the western states has been met by hydroelectric facilities but fewer economically justifiable hydroelectric developments remain for the future, and a greater share of electricity production must come from thermal power plants. The Regional Advisory Committee has projected that electricity production from such sources will increase by a factor of about seven during the next 20 years. Coal and nuclear fueled plants are expected to satisfy most of the increased requirement. Most of the nuclear generation

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[1] "Problems of Electrical Power Production in the Southwest," Hearings before the Committee on Interior and Insular Affairs, United States Senate, 92nd Congress (1971).

[2] Advertisement in *The New York Times*, Thursday, May 20, 1971, sponsored by: Black Mesa Defense Fund. (reprinted in the Senate Hearings, reference 1)

will be installed in California and the Pacific Northwest. Coal burning plants are expected to be built outside the California Subregion and about half of the future increase in coal fired generation in the Rocky Mountain area is planned to serve loads in California."[3]

From an Indian woman:

"The Earth is our mother. The white man is ruining our mother. I don't know the white man's ways, but to us the Mesa, the air, the water are Holy Elements. We pray to these Holy Elements in order for our people to flourish ..."[4]

From a druggist in Page, Arizona.

"I would like to remark here, it is not in the statement, but I am proud of our nation as an industrial complex, very proud.

"We do not dare stop this forward progress. We must continue to create new jobs for the upcoming generations. Without electric power this cannot be done. We must have production with controls.

"We have faith in our industrial community and in the Federal Government which is a participant in this project. We know that through their continued efforts and our continued demands that pollution from the burning of fossil fuels can and will be controlled and that the Navajo generating station will be the model plant of its kind in the industry."[5]

The hearings testimony runs the gamut from emotion to reason, doubt to belief, outrage to approval. There were facts enough to support any view. Smoke and haze in the once-clear desert skies. Landmarks, like Shiprock and the Sangre de Cristo Mountains, sometimes obscured. High-voltage transmission lines strode across the countryside, strip mines opened gashes in the earth, and a long pipe carried coal mixed with precious water from mine to plant.

Not all the changes were negative. Many of the local people favored the power complex. They could see new tax revenues coming in and new jobs, welcome sights in a region officially classified economically depressed. If they looked further ahead, they could see growth — more buildings and industries served by the electric power and more people fed with crops grown with the water that could be pumped from the Colorado River by this power.

The controversy is fascinating and well-documented in "The Southwest Energy Complex" by Malcolm F. Baldwin.[6] Although "ancient history," it's an unfinished history that previews the many similar "shootouts" that will occur in the future. Its ingredients include almost all the facts and trends, fears and opinions that fuel the "Great Energy Debate" we are now engaged in. For this reason, we briefly summarize what Four Corners was all about and point to the further developments and similar issues that you, as teacher and citizen, will face in the next decade.

Coal, Electricity, Air, and Water

As the old Navajo woman said, air and water are Holy Elements to the Indians. The white man sometimes seems to give almost as much reverence to coal and electricity. It is around these four elements the Four Corners controversy swirled.

They dictated the choice of the Four Corners region. There was coal there, as much as 107 billion tons, accessible to strip mining. (This is 200 times as much coal as was consumed in the United States in 1970.) There was water, not a lot, but apparently enough. There was air, rural air over which air quality controls were not terribly stringent. There was a demand for electricity.

Figure 1, which shows the locations of the six controversial plants, sets the story. Since these are generating plants, some idea of their size is necessary. The Phase I development in the area (to be complete by about 1975) is expected to provide about 7,000 million watts (Mw)* generating capacity, almost enough electric power for the City of New York. The Phase II development, to be complete by 1980, will roughly double this capacity.

The Four Corners Plant, the first to be built, was a business success from the beginning. The cost of energy from the strip-mined coal was the lowest of any steam plant in the country. This success encouraged other utilities of the Western Energy and Supply Transmission Associates (WEST) to undertake development of the six plants shown in Figure 1. Then the storm broke.

The objections to the Four Corners Plant, and to the others that followed, can be classified under four categories: air pollution, water rights, strip mining, and politics and economics. We will look briefly at each of these and at the different points of view regarding them.

Air Pollution

The first Four Corners Plant units were built in the early 1960s, before the national sensitivity to air quality that led to the Clean Air Act of 1970. The plant had emission control over the "particulates," the small soot and ash particles which go up the stack. The early control units were not very efficient, however, and the Four Corners Plant sent an enormous plume of smoke billowing out through those once clean desert skies. The

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[3] Staff report on "Electric Power and Related Developments in the Black Mesa and Four Corners Areas," Division of Electric Resources and Requirements, Federal Power Commission, May 24, 1971, reprinted; Senate Hearings (see reference 1).

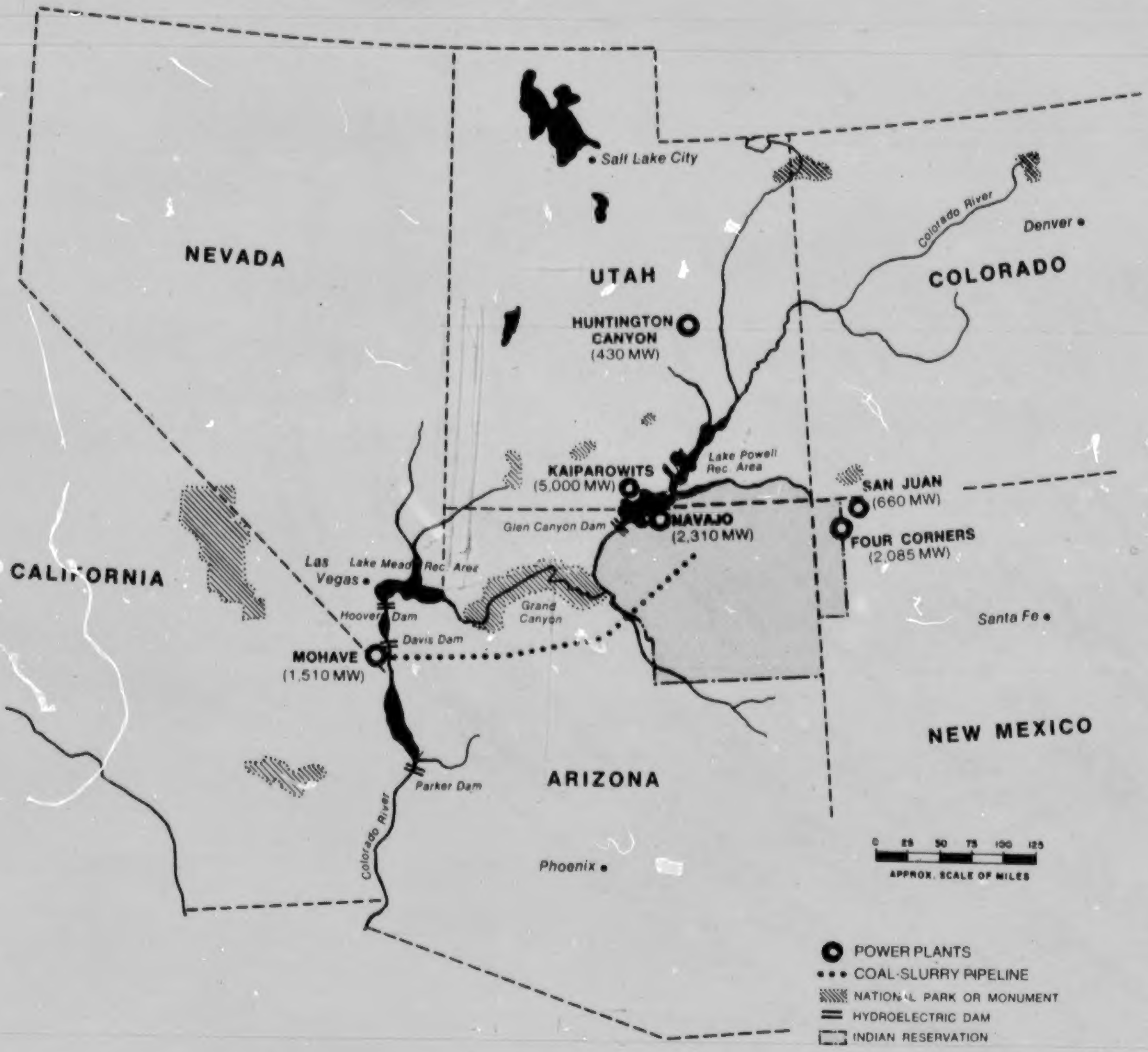
[4] Statement by Asa Bazhonoodah (83-year-old Navajo woman), reprinted in Senate Hearings of reference 1, pg. 1550

[5] Statement by Mack Ward, druggist, Page, Arizona, Senate Hearings, reference 1, pg. 1547.

[6] "The Southwest Energy Complex: Policy Evaluation," Malcolm F. Baldwin, The Conservation Foundation, Washington, D.C., 1973.

*A watt is a measure of electrical power, the amount of electrical energy which must be continuously provided to a load. A million watts is about the power necessary to light a large sports stadium.

FIGURE 1
Utility and Coal Projects in the Four Corners Region


Salt Lake City
NEVADA
UTAH
COLORADO
Colorado River
Denver
HUNTINGTON CANYON (430 MW)
Lake Powell Rec. Area
KAIPAROWITS (5,000 MW)
SAN JUAN (660 MW)
NAVAJO (2,310 MW)
Glen Canyon Dam
FOUR CORNERS (2,085 MW)
CALIFORNIA
Las Vegas
Lake Mead Rec. Area
Grand Canyon
Hoover Dam
Santa Fe
Davis Dam
MOHAVE (1,510 MW)
NEW MEXICO
ARIZONA
Parker Dam
Colorado River
Phoenix
0 25 50 75 100 125
APPROX. SCALE OF MILES
POWER PLANTS
COAL-SLURRY PIPELINE
NATIONAL PARK OR MONUMENT
HYDROELECTRIC DAM
INDIAN RESERVATION

plume was tracked by private plane for 150 miles or more.[7]

The output of particulate matter from the Four Corners Plant was reported as 350 tons per day, almost three times the total particulate emission of Los Angeles. The emission of smog-forming sulfur dioxide, 320 tons per day, was about one and one-half times the Los Angeles total of 225 tons per day.

The imposition of more stringent air-quality standards caused the addition of more efficient emission controls to the Four Corners Plant and will require their installation in the other plants of that area. However, although it is possible to remove most of the particulate matter (and the present devices now remove better than 99 percent of them), it is more difficult to remove the sulfur dioxide. The "wet scrubbers" on the Four Corners Plant that remove the particulates, also remove 20 to 30 percent of the sulfur. Fortunately Western coal is generally low in sulfur. The nitrogen oxides, which form the eye-burning photochemicals in the Los Angeles smog, are not removed.

If the air pollution control equipment of these six plants performs up to expectations, the pollutant output from these plants will be as follows:

particulates	73 tons per day
sulfur oxides	942 tons per day
nitrogen oxides	1,701 tons per day

These totals are roughly comparable to present daily emission from Los Angeles *and* New York City.[8]

We have mentioned one of the visible effects of this pollution: The magic clarity of the desert air has been lessened. The turn-on of additional plants will increase the haze. Other effects are to be expected. These pollutants can harm plant and animal life; sulfur, for instance, can combine with water vapor and form sulfuric acid. The acidity of Lake Powell will have to be watched.

As always there may be surprises. There is some indication that the smoke and ash settling in the desert is increasing fertility. Vegetation near the plants is showing increased growth.

Water

Power plants need water as well as air. Their major requirement is for cooling water; the least expensive means of cooling the condenser (in which the steam exhausted from the turbine is changed back to water) is to pump water through it. Sufficiently dear in this arid region, water is recycled at most of these plants through cooling towers and back to a cooling pond. Nonetheless, by 1980 these plants may consume (by evaporation from cooling towers and use in ash removal) a significant fraction (perhaps 10 percent) of the area's available water. In fact, water demand throughout the region is increasing, driven by the same growth that is causing the rising demand for electric power.

Water and electric power are directly related; some of the power generated will be used to pump water from Lake Mead for irrigation. We will not try to make this argument quantitative, to add and subtract the estimated acre-feet of water needed for the various uses. At present, however, it is the lack of water rather than worry about air pollution that is slowing approval of the huge Kaiparowits Plant in Utah.

Water is a more crucial problem for the Mohave Plant, which is fed by coal shipped by a 276-mile "slurry" pipe from the Peabody Black Mesa mine. The coal from the mine is crushed, mixed with water, and then pumped to the Mohave Plant. Since Peabody was prohibited from taking ground water at levels above 1,000 feet (this would interfere with the supply of water to Indian wells), the company has sunk six deep wells, to depths of about 3,600 feet, to tap a large reservoir of clean, fresh water. Encased to prevent connection with the upper reservoirs, these pumps, at full capacity, are capable of drawing 1,500 gallons per minute. There has been concern that the depletion of the lower water table would affect the upper level, but monitoring of the Indian wells and ground water levels has not shown any effect so far.

Strip Mining

What makes the Southwestern coal so attractive, in addition to its abundance, is its nearness to the surface. It lies on the Black Mesa, less than 100 feet below the surface, easily reached by the huge "draglines" (mechanical scoops) that operate in the mine.

It is the use of large-capacity equipment that makes strip-mined coal the least expensive on the market. The technique of strip mining is like deep plowing. The soil and rock above the coal (the overburden, as it is called), is removed in a long trench, the coal extracted, and the overburden from a parallel trench is then dumped in the first one. The topsoil is thus buried under 50 or 100 feet of subsoil. In some parts of that arid land the term "topsoil," of course, is meaningless. Peabody Coal Company, for instance, reports that tests at their Black Mesa mine show that the fertility of the subsoil is as good as (or better than) the sandy top layer.

The amount of land involved is impressive. The Peabody Company will have to strip about 400 acres a year to provide the 40,000 tons of coal a day needed to fuel the Mohave and Navajo Plants. During the projected 35-year operation, about 14,000 acres, a little less than one percent of the Black Mesa, will be strip mined. If the Utah International Coal Company, which provides coal for the Four Corners Plant (from a nearby mine), and the San Juan Plant mine are as productive, then the total land stripped annually in this region will be nearer 800 acres. What this stripped land will look like five or

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[7] Testimony by Dr. Joseph J. Devaney, President, Anti-smog Federation, Los Alamos, New Mexico, Senate Hearing, reference 1, pg. 117.

[8] The two-city totals are: particulates — 323 tons; SO — 1,290 tons, and NO_x — 2,291 tons. "Descriptions and Emmissions Data on the Six Power Plants Concerned with the Four Corners Area. Data Comparisons with New York City and Los Angeles," WEST Associates Information Office, Salt Lake City, Utah, 1971.

10 years from now is difficult to judge. It will depend on regulation, motivation, and on climate and other factors controlled by nature. With the best of intentions, this dry land will be hard to reclaim. Rain is scarce and such rain as does come carries with it the danger of washing saline shale down into the surrounding land. Dust will also be a problem.

Regulation, which differs from state to state, is becoming stricter. Utah International's lease with the Navajos, drawn up originally in 1957, was much more permissive than the Peabody lease with the Hopis and Navajos on the Black Mesa.

Attitudes of companies differ also. At last report,[9] Utah International had regraded only 100 of 1,400 disturbed acres while Peabody had already graded and reseeded 300 or so acres from the much smaller total on the Black Mesa.

The Peabody reclamation effort is costing about $2,500 per acre to regrade and another $50 or so to spread 25 pounds of alfalfa, clover, and native grass seeds. It is too early to see how full the recovery will be.

Men, Money, and Politics

In addition to the environmental effects we have described, the "labor pains" of the Southwest power complex involved men, money, and what sometimes seemed to be cross purposes of several Federal Government agencies. We will find these components interacting again and again in similar issues to be faced elsewhere. A brief résumé of the setting and some of the action will preview this dimension also.

Money: There is, of course, money to be made from the Southwestern coal. At Black Mesa alone coal should gross a billion dollars, more or less, for the Peabody Company over the 35 years of contracts with the Navajo and Mohave Plants. There is money also for the Hopi and Navajo tribes. Their royalties of 20 to 25 cents a ton (with an escalation clause if the price of coal continues to rise) are already bringing in a million dollars a year and are expected to average $3 million a year during the duration. For these some 125,000 Indians, this amounts to $24 per year. The annual Peabody payroll of $4 million makes a much bigger contribution to those Indian employees who make up 80 percent of the work force.

In New Mexico, the net return to the state and to the Navajos from the utility operation there, was estimated in the Senate Hearings as follows:

Investment	$294,620,000
Employment	532 (50 Percent Navajos)
Payroll	$5,900,000 Per Year
Rents & Royalties to Navajos	$1,180,000 Per Year
Taxes	$1,145,000 Per Year
Materials & Supplies Purchased in New Mexico	$1,300,000

Energy and Indians: The philosophical differences between the goals and values of the Page, Arizona, druggist,[5] and those who bought the advertisement in The New York Times,[2] was mirrored within the Hopi and Navajo tribes. To the Tribal Council, the plants and mines offered a way out of economic misery. To other Indians, it meant leaving the traditional paths of their people. This latter view was expressed at the Senate Hearings by a young Navajo:

> *"The Government says that we are economically underdeveloped and that we should all be overweight and have health problems like the white people. They look at our resources and justify that a good way to become economically viable is to develop our resources. Have they ever thought that the Navajos don't like to be up with the national standards in economics, education, employment, et cetera. We don't like this idea of keeping up with the Joneses as the white man does, but we want to develop at our own pace. This is the white man's invention, to keep up with the Joneses."*[10]

We will see the same controversy open again in the Northern plains where a large coal-electric complex is being planned and where Indian land and water rights are deeply involved. It will be important for our national conscience to make certain that our need for energy does not come at the expense of the Indian and thus add another unhappy chapter to the others that describe our dealings with these original Americans.

Policy and politics: The plans for the Southwest power complex began slowly, took nourishment from different sources, and urgency from different needs. They involved not only the utilities, but several Federal agencies as well. These agencies came in at different stages in the project development and had different roles.

A feature of Four Corners development, and the controversy that surrounds it, is that most of the Federal agencies involved are part of the Department of the Interior. A partial roll call includes the Bureau of Reclamation, the U.S. Geological Survey, the Bureau of Indian Affairs, and the National Park Service. The Clean Air Act and the other antipollution laws of the late sixties and early seventies gave the Environmental Protection Agency a piece of the action. Since many of these same agencies will be involved in future energy-environment issues, we can benefit from an examination of their role.

The lead agency in many ways, the Bureau of Reclamation, had been working for several decades to spur the economic growth of the Southwestern Colorado Basin region. It had proposed the two dams on the Colorado, above and below the Grand Canyon, for instance. (This idea was eventually rejected.) The plan to develop coal resources and build generating plants was, therefore, quite consistent with its goals.

The other agencies are charged, in one way or another, more with protection than with development.

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[9] "The Southwest Energy Complex," op. cit., pg. 29.

[10] Senate Hearings, op. cit., pg. 1553.

The Bureau of Land Management, for instance, is charged with supervising strip mining, and, in general, with assuring that proper "land management" occurs. The Bureau of Indian Affairs supervised the coal lease and water rights negotiations with the Indians. The National Park Service has obvious responsibilities in an area that includes many national parks and monuments. The Environmental Protection Agency's chief concern is defining air-quality standards and supervising the data gathering.

The main complaint about the way these agencies carried out their responsibilities is that the agency that was supposed to push, did, but that the agencies charged with protection were not as aggressive. The Bureau of Reclamation, for instance, has been faulted for a single-minded commitment to its long-term plans for bringing irrigation water to central Arizona. Alternatives, critics claim, such as less economic growth or patterns less dependent on Colorado water, have not been given serious consideration.

Critics also point to the lack of muscle in the Bureau of Land Management's strip-mine supervision, to the National Park Service's failure to protect vigorously the areas under its jurisdiction, and to the Bureau of Indian Affairs for its eagerness to accept the power complex as part of its plan to change the Indian's lifestyle.[11]

It is neither simple, nor useful, at this date, to try and analyze various agency actions and inactions. Little would be gained from opening up all of those interlocked decisions and defenses. Because the Four Corners controversy may well preview similar issues, however, it may be useful to repeat a criticism here, not of the content of the decisions, but of the structure of intragovernmental decision-making process.

In any complex and technical issue, such as the one we have been describing, much of the information pertinent to decision-making is held by government agencies. If the public is to play a role in these decisions, it must have access to this information. More important, if there is disagreement among the Federal agencies, they should be allowed, even encouraged, to make open advocacy of their point of view, and to express their doubt and concern about alternative plans. When all the agencies are within one department, as was the case in this instance, the provision for such public debate is apparently a difficult matter.

Debate over alternative plans must not only be open, it must come early if it is to be constructive. The first phase of the Southwestern power complex development was almost completed, and the second phase already underway with tremendous economic momentum, before the plan and the assumptions behind it were brought to public view.

Early, open planning will assume more relevance in future energy-environment issues. The greatest fraction of our remaining unexploited energy resources (coal, oil, gas, oil shale, and uranium) is on Government or Indian-owned land. Since the final decisions as to the use of these resources and the safeguards for the land and people will shape a generation's living, it is important that new "Four Corners" issues be identified and the discussion begun at once.

Four Corners as a Preview

We have sketched the clash of priorities, values, and needs dramatized by the Four Corners controversy in order to preview both the Source Book and the future issues with which the Source Book deals. Four Corners raises a series of questions that will be raised again. Many of these are questions of national priorities and of the rights of minorities in the face of majority need.

The Four Corners area, after all, has two outstanding assets: scenery, whose sweep is enhanced by haze-free air, and those large shallow deposits of coal. Who is to decide which of these is of highest priority? Can the decision be made solely in the marketplace? It was in large part their economic clout that enabled the residents of Los Angeles to have their cake and eat it, too: to demand rapid growth in electric generating capacity and to forbid the construction of fossil fuel-burning plants in their own neighborhood. On the other hand, the weakened economic situation in the Four Corners area caused some citizens of the Southwest to place a greater value on coal and electricity than on scenery, clean air, and the lifestyle preferences of some Indians.

This scenario has larger echoes. Take, for example, the Four Corners Power Plant which burns New Mexican coal. The plant's effluent pollutes New Mexican air and the strip mining of coal disfigures New Mexican land. Only 10 or 15 percent of the electric power generated by this plant, however, is used in New Mexico. New Mexico's plight is not too different from that of the world's industrially underdeveloped countries.

What has happened at Four Corners will happen again with different characters and slightly differing plots. The constant common denominator will be the pressure of energy demand. We'll sketch some of the issues now before us, or soon to be before us, which will show similar complexity.

"Cowboys and Indians": A similar conflict of priorities is building on the North Central Plains of Montana, Wyoming, and the Dakotas. The Indians are involved again, but this time the "cowboys," or at least many of the local ranchers, are their allies.

The North Central Plains boast a coal lode even greater than that in the Southwest; 40 percent of the nation's coal reserves, much of it suitable for surface mining. The plans for power development in this area are correspondingly larger. They call for the construction of 42 mine-mouth generating plants, whose locations are shown in Figure 2. The projected generating capacity is 50,000 Mw by 1980 and 200,000 Mw by 2000. The magnitude of the generating capacity designed for this area can be put in perspective by comparison. Only the U.S.S.R., the United Kingdom, and Japan presently have larger total generating capacities. Japan's capacity in 1968 was 52,650 Mw.

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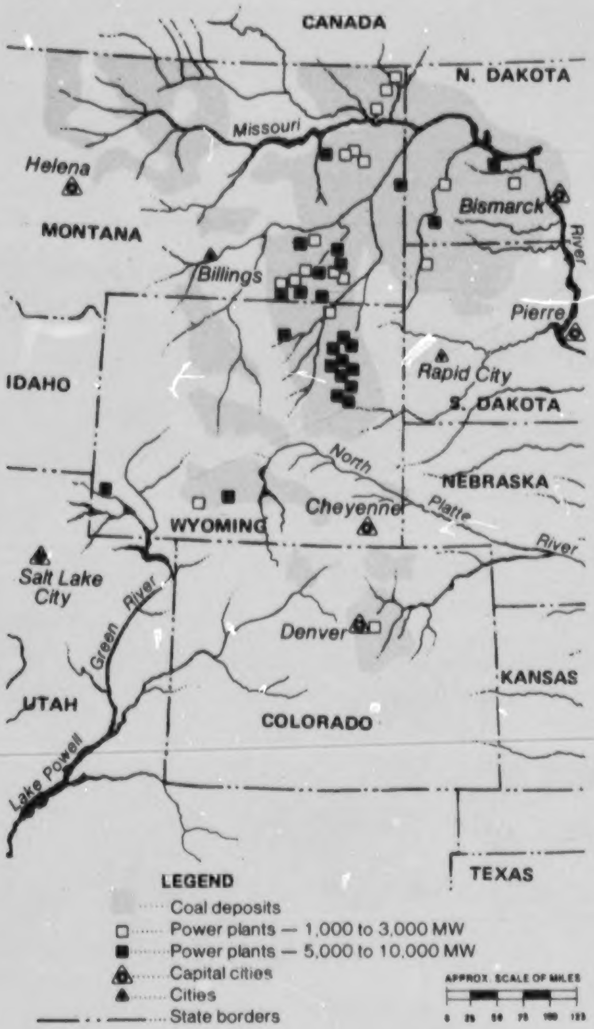
[11] For a more complete critical treatment see, for instance, "The Southwest Energy Complex," op. cit., pg. 32-44.

Some of these plants will be designed to generate 10,000 Mw each, more than enough power for all of New York City. They will be joined by equally huge coal gasification plants. We will see the problems of Four Corners magnified in the North Central Plains; more water will be needed, more land will be stripped, and more pollutants will need to be disposed of. The same clash of priorities will occur between the local desires of the Indians and ranchers, who own and love the land, and the residents of distant Midwestern cities, who need the energy that will be produced.

Mining the mountains: Similar problems, and a need for early and open planning, will occur in the "Green River Formation" of Colorado, Utah, and Wyoming where an enormous potential of oil is locked into the oil shales that make up many of those lovely mountains. This land has recently been opened to leasing and pilot plants to extract the oil are being planned. It is almost too late to ask ourselves, "Should we do this?" It is not too late to ask, "Are we doing it in the best way?"

FIGURE 2
Utility and Coal Projects in the North Central Plains



Derricks in the Atlantic: The unrelenting pressure of our need for oil and gas is driving the oil derricks out to sea. The moratorium on oil production on the Pacific Coastal Shelf has been lifted. Pumping has continued steadily in the Gulf of Mexico. Now plans are being readied for the opening of the Atlantic Continental Shelf to leasing, exploration and drilling. The ocean is a very different sort of environment from Four Corners, the North Central Plains, and the Colorado Hills. Instead of arid plains, mountains, and desert, the environment at risk here is the biologically rich coastal waters, the food bin and hatchery for ocean life. There are also questions to answer about the change in community structures and the loss of agricultural land that will occur.

Here, at least, the priority decisions will be out in the open. The oil wells, and any damage they cause, will be visible from the playgrounds of the metropolitan areas that demand their energy.

Ports and supertankers: Even with a greatly increased pace of exploration on and off the continent, the United States will not, for five or ten years, be able to satisfy its projected need for oil from domestic sources. It will take at least that long to bring new wells into production or begin commercial exploitation of the oil shale. The extra oil and gas, in ever larger quantity, will have to come from foreign sources.

Our short-term lifeline will be constructed of supertankers commuting with oil from the Persian Gulf and of refrigerated tankers bringing liquified natural gas. We will need new deep ocean ports, onshore storage, and refining facilities to service them. We will have to solve yet another set of priority questions about the use of coastal lands.

The breeder reactor: We are presently committed, by AEC (Atomic Energy Commission) policy and the President's order in the June 1971 Energy Message, to the development of a new type of nuclear reactor, the breeder reactor, which will greatly increase the amount of energy we can get from existing uranium ores. To the already considerable controversy over the dangers from present-day nuclear plants, the breeder will bring its own topics. We must be prepared to handle not only increased production of radioactive waste and the unique health hazards of plutonium, but also a different sort of problem opened up by the shipment of large quantities of bomb-grade plutonium.

The Great Energy Debate

The coming policy issues we have just described are all part of a continuing "debate" that will occupy us for the next several years. With the oil embargo serving as a convenient marker, we have crossed over into a new era. We have left, perhaps forever, the era of inexpensive energy and are now faced with shortages and higher costs of energy and with the need to pay for the heavy burden we have put on the environment.

In this democracy, if it is to survive, it is necessary that all citizens participate in "debates" of such pervasive importance. It is also necessary that the ultimate decision be fashioned from as thorough an understanding of the issues as is possible. It is toward the fashioning of that understanding that this Source Book is designed.

The Source Book

There are two categories of knowledge that must underlie a thorough understanding of the issues in this debate. There are the scientific and technical issues and the economic/political/societal issues. We underline these categories by dividing the Source Book into two volumes.

Volume I deals with the economic/political/societal issues. In it we describe the economic and environmental costs of producing and consuming energy. We also describe the way in which energy decisions are interlocked with such issues as inflation, employment, the balance of trade, and foreign policy. We look at energy policy in this country and the roles of government and the "energy companies" in forming and making that policy work. We look at the collision between "no-growth" and "dig and drill" philosophies, and at the regulations, taxes, consumption patterns, and lifestyles which each policy assumes.

Volume II provides the scientific and technical background that is needed for a thorough understanding of the issues in Volume I. In the second volume we describe energy, where it comes from, how it is converted to our use (and with what efficiency), and how much of it still remains in the stockpiles of the fossil fuels (coal, oil, and natural gas) and uranium. In this volume we also examine the flow of energy through our society, the end uses that take the largest share, and their patterns of growth. In the last two chapters we probe the developing technology that will give us the ability to use our present fuels more flexibly and efficiently, and may open new and larger sources of energy.

Using the Source Book

We have written this Source Book for classroom teachers, hoping to provide the content from which they can design useful learning experiences for their students. It is these students, now in your classes, who soon will be the decision-makers, and participants in the Great Energy Debate.

It must be emphasized that this is a Source Book. It is not a reader, a policy statement, or a polemic for a particular course of action. While the two volumes' chapters follow sequentially, it is not necessary to read them that way. It is likely, for instance, that social studies teachers, and those from the humanities, will find themselves most at home in Volume I, while science teachers will be more comfortable in Volume II.

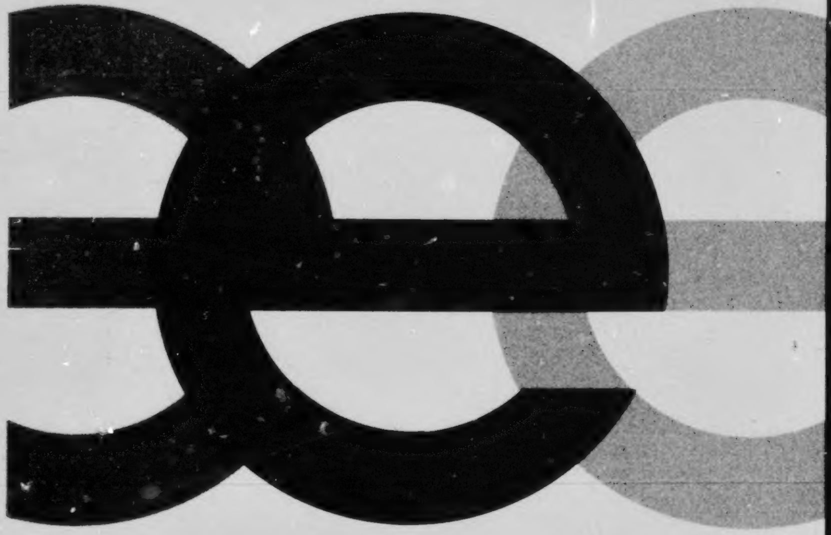
If, however, these volumes are only considered from a narrow discipline-determined viewpoint, we will have failed in what we set out to do. Energy-environment problems are necessarily multidisciplinary. They cannot be handled as a set of scientific facts, nor can they be dealt with in purely qualitative terms without facts or numbers. We hope that science teachers will select topics for classroom use from the Source Book which help them teach their science. We also hope they will inform themselves and their students of other dimensions of these topics. We hope to have given the social studies and humanities teachers an incentive to bring some science (and perhaps some science teachers) into their classrooms.

We *hope* that teachers will find the topics sufficiently compelling, and the writing sufficiently interesting, to warrant reading both volumes. We *expect* however that busy teachers will select from the menu presented, picking chapters and even topics, here and there, as the need and interest arise.

As befits a Source Book, we have aimed at a complete collection of the data-base for the energy debate and provide a wealth of tables and graphs in Volume II. We want to emphasize that this technical volume can be read at different levels, qualitatively to get the perspective or quantitatively to get the numbers and sizes. We have also added, for those who wish to go deeper, several Technical Appendices which give more scientific definition to certain important topics.

For many of you we have "told you more about energy than you wanted to know" (to paraphrase the little girl's report on a book about elephants); for others, perhaps, "everything you ever wanted to know, but were afraid to ask." But this is part of the message, these issues are enormously complex. Few will want to meet them head on, most will only want a piece of the action. We have tried to provide the pieces. It is now up to you to provide the action.

ENERGY-ENVIRONMENT SOURCE BOOK



Volume 1

Energy, Society, And the Environment

CHAPTER 1
Evidence of Crisis

Evidence of Crisis

"...the United States has entered a new age of energy, and we have not yet adjusted our habits, expectations, and national policies to the new age. The Arab oil embargo, while it lasted, made us keenly aware that in twentieth century America, a fourth essential has been added to the age-old necessities of life. Besides food, clothing, and shelter, we must have energy. It is an integral part of the nation's life support system. And we can no longer expect to get it with so little trouble and expense as we did in the recent past."[1]

The report by the Energy Policy Project of the Ford Foundation, from which this quotation is taken, is one of a long shelf of books that deal with the energy problem or one of its many facets. Although the energy crisis has now lost its dominant position in the media to the economic crisis, it is still very visible in newspapers and magazines, on non-fiction booklists, on television, and in the titles of conferences and topics of after-dinner speakers.

The energy crisis is wide and long. It is as wide as our day-by-day lives and the environment we live them in. It is at least as long as this century; for many of us, as long as our lives. It will grow slowly from crisis to crisis, and our responses will be slow to show effect. It cries out now for our understanding and action.

In this Source Book we will emphasize understanding, a challenging task in itself, for an energy source book must cover a broad range of topics. We will not speak directly to the need for action other than to describe some of the paths through the future that have been suggested.

As we said in the Introduction, this first volume will deal primarily with the descriptive aspects of the Energy Crisis. There will be quantitative detail, but most of the hard data is gathered in Volume II. We will use this first chapter to overview this multidimensional crisis, providing both a preview and summary of both volumes.

The Crisis Past

On October 17, 1973, most of the oil producing countries of the Mideast placed an embargo on oil shipments. The shock waves from this action reached around the world and were followed by economic and social disruption in most of the industrialized nations.

The valves were reopened in March 1974. Oil began to flow again, but the world was no longer the same. The energy crisis was upon us, of course, before the oil flow was shut off. With oil flowing it is still upon us. The embargo was an exclamation point, a dramatic dividing line between the era of cheap energy and the expensive present and future. It was also an unplanned (and unpleasant) experiment from which there are lessons to be learned. It brought the role of oil in our lives sharply into focus.

Less Oil and Lessons

In 1972, this country produced petroleum products at an average rate of 11.2 million barrels per day (M bbls per day) and consumed them at a rate of 16.4 M bbls per day. We imported 5.2 M bbls per day, 32 percent of total consumption. By September 1973, the gap between production and demand had risen to 8.6 M bbls per day. At that time we were importing 40 percent (3.47 M bbls per day) of our crude oil,* 40 percent of our fuel oil (2.14 M bbls per day) and smaller percentages of gasoline and jet fuel (kerosene).

The oil embargo imposed in October 1973 was not immediately effective. Tankers were already at sea, and there was oil in the refineries and storage facilities of other countries. In February 1974, however, when the effects of the embargo were most strongly felt, imports of petroleum products were 3½ M bbls per day below the projected demand. They averaged 1.9 M bbls per day below projected demand for the entire October-to-February period. In terms of percentages, domestic oil consumption was reduced by a high of 17 percent in February and by 10 percent over the entire embargo period.

Since oil supplied 46 percent of our total energy in 1973, at the depth of the shortage our total energy consumption was reduced only 7.8 percent. What was the reaction to this reduction? What were the effects?

The Federal Government, with neither stored oil nor immediately accessible oil reserves, met the shortage with the only programs that could have immediate effect, allocation of petroleum products and a call for conservation. A fairly successful attempt was made to give industry the energy it needed. The burden of both these responses fell largely on the residential and commercial sectors.

The major components of the conservation response were lowered highway speed, voluntary reduction in travel, and reduction in home heating by thermostat setback. These voluntary reductions were backed up by reductions in the quantity of gasoline and fuel oil available to the individual consumer. There was also a call for voluntary conservation of electric power.

Such data as are available show that these programs had measurable effects. Consumer energy purchases (chiefly gasoline and fuel oil) dropped by almost 40 percent in the first quarter of 1974. The number of automobile trips declined and the average household temperature during the 1973-1974 heating season was 68°F, two degrees lower than the previous season's average. Electricity consumption showed the most dramatic response. Growth for 1974 slowed from its historic rate of 7 percent per year to almost no growth (0.6 percent per year). In addition to consumer conservation, the mild winter and the beginning recession contributed, apparently, to this slowed growth. The resulting cash flow reduction sent several utilities to their state regulatory commissions with requests for rate hikes. The economy was affected in other ways, also.

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[1] "A Time to Choose," Final Report by the Energy Policy Project of the Ford Foundation, Ballinger Publishing Co., Cambridge, Massachusetts, 1974, pg. 1.

*Crude oil is oil before refining, essentially as it is produced at the well.

Economic effects: Several measures of the economic effects of the embargo are now available. The Gross National Product, the GNP, that magic measure of prosperity, declined from its high of $1,359 billion in the fourth quarter of 1973 to $1,344 billion in the first quarter of 1974. It is difficult to determine what fraction of this was due to the embargo, but comparisons of forecasts before and after the embargo suggest that it carried a penalty of about $15 billion.

The economic penalty was apparent also in personal spending, where in addition to energy, which we have mentioned, expenditures for automobiles declined (40 percent in the last quarter of 1973 and 10 percent in the first quarter of 1974). The sales of new cars decreased by 34 percent in the first quarter of 1974 (as compared with 1973). The decrease was specific; the small cars increased their 1973 total sales by 29 percent while standard models dropped 21 percent. The consumer paid more for all goods, and about one-third of this inflation was due to increases in energy prices.

Unemployment rose by 500,000 during the embargo period; 150,000 to 225,000 of those out of work were employed in gasoline stations and airlines, which were directly affected by fuel shortages, and the other 300,000 or so were largely in the automobile and automobile-parts industries. The recreational vehicle business was hard hit. One-quarter of the gasoline service stations (60,000) closed or changed owners in 1973. Hotels and motels also showed losses.

Other effects: There were other effects that remind us of the interlocking relationships of all the components of the economy. The oil embargo kept many people alive; auto fatalities decreased by about 25 percent during the embargo period due to lower speeds and less travel in general, an estimated saving of 4,775 lives. On the other side of the ledger are the losses in revenue from state gasoline taxes. The estimated loss from projected tax revenues (which were based on a continuing increase) is predicted to be $700 million.

The embargo as preview: The brief duration of the actual shortage, the cooperation of the public in conservation measures (aided by the mild winter of 1973-1974), and the relative success of allocation programs considerably softened the effect of the embargo on the economy. There were, however, lasting effects. Energy prices rose — almost doubled — and show no signs of falling. The car buying habits of many Americans have been changed, probably permanently. The independent gas station ("gas for less") has just about disappeared.

There were other effects which are difficult to quantify. Energy seems to have temporarily gained priority over environmental concern. Air quality standards are being revised to allow high sulfur fuels to be burned for electric generation. The implementation of auto emission standards was postponed.

We also became aware of the subtle connections between energy and our economic health. Plastics became scarce along with their oil-derived raw materials. Employment dropped not only in the key industries we have mentioned but also in the aircraft and boat industries, in the dry cleaning and laundry business, and even in real estate. Perhaps connected with this latter decline, a shift away from suburban home buying and a move to multifamily housing nearer to the city seems to have begun.

Although the oil embargo was an artificial crisis of short duration, it caused many of us for the first time to look closely at this web that energy traces throughout our daily lives. In the remainder of this chapter we will briefly summarize the energy picture as it now looks in the waning months of 1974 and trace some of the threads of this web.

Where We Are Now

How much energy are we now using? What are we using it for? Where does it come from? A description of the present must begin by answering these questions. We also will look briefly at growth in energy consumption and identify the areas of immediate critical concern.

Supply and Demand

In 1973 the average per capita consumption* of energy in this country was 250,000 Calories per day, and the total for the year was 18.9 quadrillion (Q)** Calories.***

The sharing of this energy between the four sectors, residential, commercial, industrial, and transportation, is shown in Figure 1-1. We also indicate in this pie diagram the important category, raw materials. Not only are chemicals made from coal tar and petroleum important in the manufacture of plastics and other synthetic materials, but tar, asphalt, road oil, and lubricating greases are also examples of non-energy uses of fuels.

In Figure 1-1 we assigned to each of the five sectors not only the electricity they used but the fuels that were used to generate that electricity. In 1973, 5 quadrillion Calories, 26 percent of the total, was used to generate electricity, but two-thirds of this energy was lost as waste heat at the power plants, so that in fact electricity contributed only 10 percent of the net energy.

Figure 1-2 gives additional information about our use of energy; it shows the percentage sharing of various end uses. About half of it was used as heat, an additional third as mechanical work in motors of various kinds (including automobiles), and the rest as lighting, cooling, etc. (A complete breakdown of the pattern of energy consumption is given in Chapter 3 of Volume II.)

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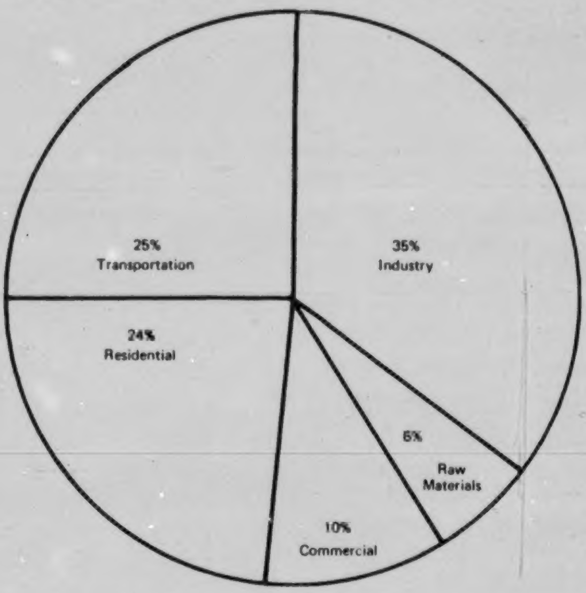
*We will follow common practice and use the term consumption but actually, as we explain in Chapter 3, Volume II, energy is not "consumed" but converted from one form to another.

**We will use the abbreviations Q for quadrillion (1,000,000,000,000,000), T for trillion (1,000,000,000,000), B for billion (1,000,000,000) and M for million (1,000,000). These abbreviations are discussed further in Appendix A2.

***These are the same Calories in which food energy is measured. We define this and other measures of energy in Chapter 1, Volume II.

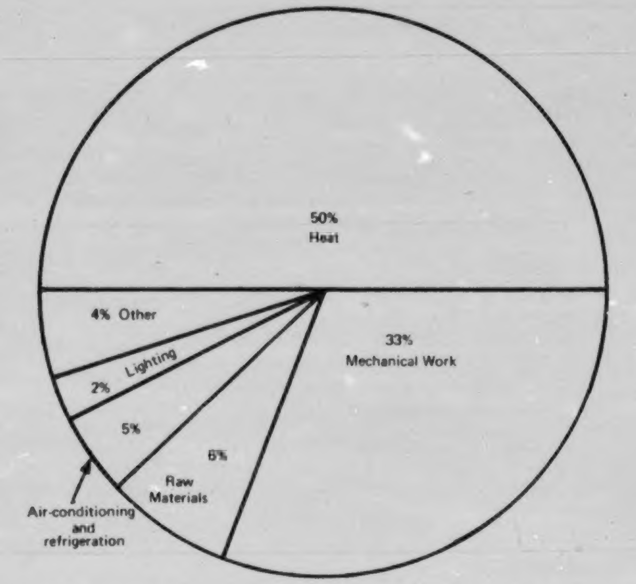
The fuel mix: We obtain almost all of this energy (95 percent) by burning fossil fuels (coal, oil, and natural gas). Waterpower (4 percent) is used in the generation of electricity and the new entrant, nuclear energy (1 percent), make up the difference. The contribution of these various sources to the total is shown by Figure 1-3.

FIGURE 1-1
Categories of Energy Consumption, 1973



Data from Bureau of Mines, U.S. Department of the Interior.

FIGURE 1-2
End Uses of Energy, 1968



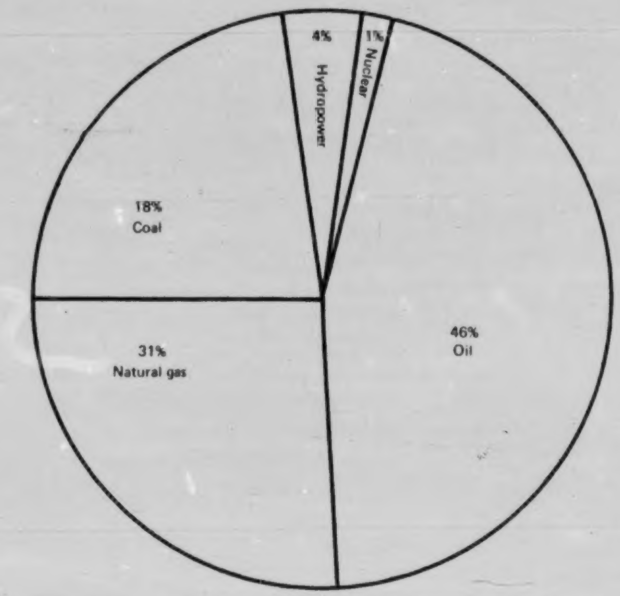
Data from "Patterns of Energy Consumption in the U.S.," Office of Science and Technology (USGPO Stock #4106-0034)

The fuel mix has changed with time. Coal, for instance, accounted for three-quarters (78 percent) of the much smaller total energy in 1920 while petroleum products only provided 18 percent; by 1950 oil and natural gas accounted for 57 percent between them and coal for 38 percent. These replacement cycles (which are described more thoroughly in Chapter 4, Volume II) continue; oil and natural gas (which provided 76 percent of the energy in 1973) are becoming scarce and expensive and nuclear energy is expected to grow. Some estimates have it providing 20 percent of our total energy and almost 30 percent of our electrical energy by 1985.

Growth: We cannot fully appreciate the energy picture with a snapshot of the present, we must look back at the past and peer into the future. Over the past several decades total energy consumption in the United States has grown, on the average, 3½ percent per year. It grew more rapidly in the recent past, averaging 5 percent per year from 1965 to 1970. On the average, therefore, our energy consumption is doubling every 20 years (every 14 years at the 1965-1970 rate of increase). We will expect to be using double the 1973 total by 1993 if the average trend continues.

This growth is not primarily due to population, which has been doubling more slowly (on a 45 year period). In fact, we have been at almost the zero population growth level since the mid-sixties. What is growing most markedly is per capita energy consumption (the total

FIGURE 1-3
Sources of Energy, 1973



Data from Bureau of Mines, U.S. Department of the Interior energy use divided by the total population). We consumed about 90 million Calories per person in 1973 and per capita consumption has been doubling every 25 years.

Although all forms of energy use have been growing, the fastest growth of all is in the consumption of electrical energy. Our consumption of this versatile form of energy has been doubling about every 10 years. If this rate of growth continues, we will need four times the generating capacity in 1990 that we had in 1970 and eight times the 1970 capacity in the year 2000.

The multitude of problems which go to make up the Energy Crisis stem largely from this rapid increase in demand. Each year we need not only to provide as much fuel as we did the year before, but more. What was enough in the 1960s will provide only half our needs in the 1980s.

Problems of Energy Supply

Energy supply is but one of the critical dimensions of the crisis, but the recent embargo brought it to the forefront. There are three aspects that deserve and are receiving our attention: the growing dependence on imported oil, a shortage of natural gas, and a threatened shortage of generating capacity and fuel for the production of electricity.

Oil importation: The United States was the first oil power and was a supplier of this liquid energy until the 1950s. The insatiable appetite of our industry and transportation for this inexpensive, easily-handled fuel, plus a slowing down (and since 1971 a decline) in domestic production, has caused us to depend more and more on foreign sources. We imported 7 percent of our total energy in 1960, 12 percent in 1970, and 19 percent in 1973. Oil was the major import (we have always exported a little coal) and the percentage of oil from foreign sources, 16 percent in 1960, rose to 23 percent in 1970 and soared to 37 percent by 1973. In 1974, in spite of a decline in total oil consumption, imports rose by 7 percent over 1973.

This dependence on foreign oil, which had economic roots (foreign oil was cheaper) now presents us with several problems. The days of inexpensive oil are over and price is now determined by decisions made by OPEC (the Organization of Petroleum Exporting Countries). More than our economy is threatened by this dependency. The embargo showed that oil can be used as a trump card in the high stakes game of international politics.

There are many factors that enter into the decision to increase imports or domestic supplies of oil. They include supertankers, new deepwater ports, oil derricks off the Atlantic beaches, and Arctic pipelines just to mention a few. Their discussion will occupy much of our attention in the chapters ahead.

Natural gas: The true harbinger of the Energy Crisis was not oil but natural gas. In the 1970s the supplies were insufficient to allow many companies to accept new customers, and several times during these past four years companies have enforced their "interruptable supply" contracts. (These are a class of contracts to bulk users that give a lower rate on the condition that delivery can be interrupted during periods of short supply.) Many schools, hospitals, and industries have been temporarily left without fuel and several electric utilities, for instance, have totally or partially converted to other fuels.

The causes and duration of the supply problems with this clean fuel are subjects of controversy. Domestic production has not increased as fast as the demand. The most often discussed cause is the regulated (and low) price of gas. The price is now rising and there is strong pressure to deregulate it. We are increasing our imports from Canada (5 percent in 1973) and looking across the ocean to Algeria and even the U.S.S.R. for more gas.

Blackouts and brownouts: While the Northeastern "Blackout" in November 1965 was not really a symptom of the energy crisis (it was a temporary shortage amplified by errors in the response of the system), it did drive home to us the importance of electrical energy. Our consumption of electricity has almost doubled since then, and although there have been no more large scale blackouts, we have begun to see "brownouts." Brownouts are deliberate responses to overdemand. The utility company, when it is pressed for more power than it can provide, lowers the voltage (and, therefore, the power supplied) to all users. Air conditioners slow down, motors labor, and electric heaters are not as hot.

We are threatened in the next few years with more of this inconvenience unless demand slackens or supply increases. There are two major factors hampering supply efforts; the utility companies are not able to build new generating capacities rapidly enough, and their fuel supplies are uncertain.

As always, a host of factors contributes to each of these problems. The building of new capacity has been slowed by controversy over power plant siting (especially nuclear plants). A shortage of money has also contributed. Cash flows and dividends are down and investor confidence seems to have been shaken by the conflicts over siting and to some extent by performance failure of the nuclear plants (which make up half or more of the new plants). The recession hasn't helped. A result has been the cancellation or postponement of 71,000 Mw of new plant capacity in 1974. (A Mw is a million watts, about the power needed to light a large sports stadium at night.) This means that 70 or so plants that would have been under construction are still on the drawing boards; 40 of these were to be nuclear and 30 fossil fuel burning.

The fuel shortage is also acute. Although there is plenty of fuel for the coal-burning plants, new air quality regulations for the 1970s deny the Northeastern plants access to the close-by Appalachian coal. (Its sulfur content is too high to allow its burning, and the technology to remove sulfur pollution from the stack gases is not yet fully mature.) In response to strict air quality regulations, many utilities converted to oil and gas only to run into shortages of these fuels. The pervasive uncertainty has caused investors to put their money elsewhere. It will take assurances of long-range coal supply and a clear promise either of ready emission control technology or relaxed restrictions on sulfur pollutants to break this bottleneck.

Threats to the Environment

We have talked so far about supply and demand, but in many ways this is the least troublesome part of the energy problem. It will take five or six years, but given the green light of money and relaxed environmental restrictions, the energy companies can close the gap. A more troublesome dimension is entered when we look at the effects on our environment of increased energy consumption and production. When we examine the interaction of energy and environmental problems the topic headings remind us of an EPA (Environmental Protection Agency) division roster. Almost all the titles are there: air and water pollution, land and ocean use, radiation pollution and other hazards of radioactive substances. We will briefly preview the major threats in each of these areas. A full discussion of their size and the hopes of lessening them takes up the middle chapters of this first volume.

Air Pollution

Air pollution was one of the early indications that we were overstressing our environment. It was called to our attention by the smog disaster at Donora, Pennsylvania, in 1948, and by the air pollution in Los Angeles which worsened steadily through the late forties and fifties.

The five air pollutants for which records are kept are carbon monoxide, the hydrocarbons (molecules of hydrogen and carbon), the sulfur oxides (molecules of sulfur and oxygen), the nitrous oxides (molecules of nitrogen and oxygen), and the particulates (soot, etc.). An estimated total of 272 million tons of these pollutants were emitted into the air from various sources in 1969.

The present front runner in the air pollution handicap is the automobile. It contributed 74 percent (by weight) of the carbon monoxide, 53 percent of the hydrocarbons and 47 percent of the nitrogen pollutants in 1970. The electric utility industries lead in sulfur pollutant emission with 73 percent and are close behind the automobile with 42 percent of the nitrous oxides. Industry leads in only one category, it is responsible for 41 percent of the particulate matter. A breakdown of the percentage of total air pollution by source is given in Figure 1-4. The hazard of pollutants does not depend on their weight, however, so we must discuss their effects separately.

Sulfur smog: The utility plant is the major producer of the sulfur pollutants which are the chemical villains of what is called "classical smog." This is the black, smelly, wintertime smog that caused the 14 Donora deaths in 1948, almost 2,000 deaths in London in 1952* and 200 in New York in 1966. These were instances of air pollution disasters. Many more deaths are attributable to the lower levels of more common exposure.

The sulfur pollutants are formed when a fuel containing this impurity is burned. The fuels can be ranked by their sulfur content; gas is the cleanest and coal the dirtiest with oil in between.

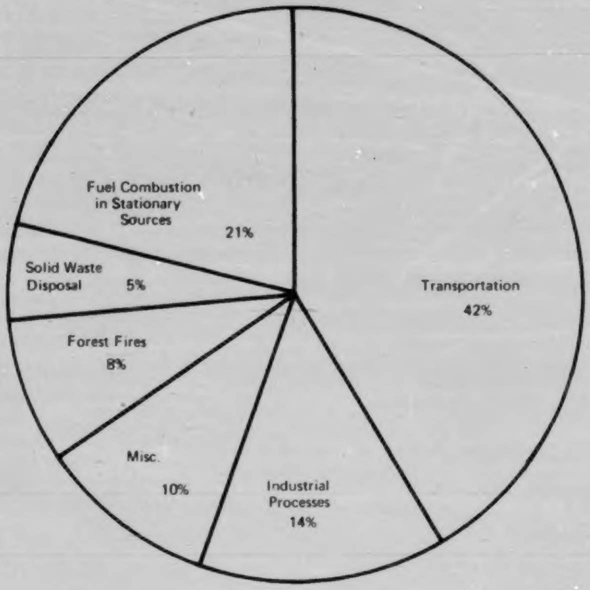
The utility plants in the fifties and sixties made great strides towards eliminating the soot and ashes that poured out the smokestacks. Similar technology for the control of sulfur emissions is not yet in large-scale use, and, perversely, low sulfur coals lower the efficiency of the "electrostatic precipitators," which are used to remove the soot. As we have said, both the utility industry and the coal industry are going through a period of great uncertainty as they wait to see whether coal can be cleaned of sulfur for its needed role in electric energy production.

The automobile and air pollution: The automobile has introduced its own characteristic smog, the "photochemical smog," which first made its irritating presence known in the air-locked Los Angeles Basin.

Photochemical smog is a chemical soup sunlight concocts from the hydrocarbons and nitrogen oxides of automobile exhaust. Its effects are not yet fully investigated. Its potential for irritating lungs and eyes is painfully obvious, however, and its effects on vegetation visible. It has not as yet been shown to be a direct cause of death.

The automobile is also responsible for two other pollutants, carbon monoxide and lead. Carbon monoxide is lethal at high concentrations and can cause distress at levels of 50 to 100 parts per million. This threshold for

FIGURE 1-4
Sources of Air Pollution



Source: National Air Pollution Control Administration, HEW.

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*The Donora and London smog was probably caused by industrial coal burning rather than by utility furnaces.

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damage is occasionally reached for short times in, for instance, automobile tunnels. Lead is released in the burning of leaded gasoline, an estimated 420,000 tons in 1968 and more and more each year since then. Since it accumulates in the body we must also watch carefully for long-range effects of the exposure of our urban population to this danger.

Photochemical smog and the classical smog are troublesome only when the "atmospheric disposal" doesn't work and our waste gases hang over our cities. We discuss the meteorological causes of this disposal failure and give more details of the costs of and the proposed cures for air pollution in Chapter 4.

Competition for Water

Water is second only to air in its importance for life. Our water supply is threatened in two ways, by consumption and by heating. The introductory essay on Four Corners provided an example of both these threats. Water is a crucial ingredient at many points along the energy web. It is used in washing coal and uranium ore. It is needed for cooling in many industries and will be a raw material in the production of gas from coal in the "gasification plants" planned for coal country.

The major use of water as a cooling medium is in electric utility plants. As we explain in Chapter 3 of Volume II, the efficiency of a "heat engine," such as the steam turbine that drives most electric generators, depends on the temperature difference between the incoming and the outgoing steam. The input temperature must be high and the outgoing temperature low. To get the low outgoing temperature, large amounts of water are circulated through the systems. The best steam turbines are only 40 percent efficient (60 percent of the energy released from the burning fuel is not converted to electric energy) and the average plant is only 33 percent efficient. Therefore, two-thirds of the heat energy available from fossil fuels (or nuclear energy) is wasted. Although some of this wasted energy goes up the stack in a fossil fuel plant, most of it (and all the heat-waste from a nuclear plant) goes into the cooling water and eventually into the river, lake, or pond from which it was drawn.

There is real concern over the effects of heated water on marine life and we will discuss these effects in Chapter 4. We will focus in this introductory chapter on the staggering amount of water that is needed.

If the temperature-rise in the water is to be held to 15°F, then a modern 1,000 Mw power plant requires almost 16,000 gallons of water per second for cooling. A nuclear plant requires somewhat more. Taking into account the mix and number of generating plants predicted for 1990, the total amount of water running through our utility plants in that year would be 350 billion gallons per day. This is more than three-quarters the total available running fresh water in this country. Of course, water can be used more than once and some 30 percent of the cooling is expected to come from seawater rather than freshwater, but this rough calculation does give a perspective on the size of this water demand. We must begin to make some choices; on many rivers there is neither sufficient water or cooling capacity for all demands to be met.

Land Use

The production and consumption of energy also presents us with difficult decisions on land use priorities. We have already been introduced to several of these in the discussion of the Four Corners controversy. We must choose between mining and other uses for the land; power plants take up space (about 400 acres for a 1,000 Mw coal burning plant), as do transmission line rights-of-way (4 million acres in 1970). We will briefly preview some of these land use decisions below.

Mining: Coal, uranium, and oil shale will have to be mined either from the surface by strip mining or underground. The amount of uranium mined is small enough to be of no great concern. Oil shale mining has not yet begun. If we do begin to mine this resource we will have to remove about seven times as much rock per Calorie as we do to mine coal. Our most serious mining problems at present are with coal.

Strip mining has left us a legacy of sterile, disordered land at the mercy of wind and rain. An estimated 1,470,000-acres were strip mined for coal from 1930 to 1971, an area of 2,300 square miles, about the size of the state of Delaware. At present, about a third of this land has not been reclaimed. Between 1975 and 1985 the amount of coal to be strip mined will double the acreage. There is hope that the impact of strip mining in the next decade will be less damaging than it was in the past. State laws have been toughened and reclamation has become an accepted practice at most mines. In fact, in 1971, 73,200 acres were mined and 94,600 acres were reclaimed (as older banks as well as new ones were graded and seeded). The arid mountains and plains that will feel the shovel in the next decade will present a more serious reclamation challenge than did the rainy Midwest and Eastern coal fields, and it may take many years (or decades) to bring them back to a semblance of their original state.

Underground mining also produces its negative effects; chiefly acid water which drains out of many abandoned mines and destroys stream life. The new water quality regulations have been forcing some improvement in this historic problem. Subsidence — cave-ins — also routinely occur and ruin the land above the mines. These costs must also be added to the coal bill.

Opening wild land: A particularly thorny problem is presented when land character is changed, when land that is in a natural state is commercialized. The Black Mesa fits that description as does some of the land in the North Central Region. The most serious present conflict is in Alaska but the opening of the Colorado, Utah, and Wyoming wild mountains and highlands to oil shale mining will present a choice of comparable seriousness.

It is not just the mining that is worrisome. The trend is more and more to on-site processing, and in the case of coal, on-site generation of electricity. This puts all the pressures of our industrial civilization on the land as well. It is clear that the special nature of the land then disappears. We will continue to be faced with this choice.

Ocean Use

There are priority decisions to be made for the oceans as well. Oceans serve as highways over which a growing number of supertankers travel with oil to supplement our domestic production. We will be using more and more of these huge tankers, some with 180-million gallon (4-million barrel) capacity. Larger ones are being built. Since we may import almost 12 million barrels of oil per day in 1985, three of these huge tankers will have to unload at United States ports each day.

The increased flow of oil across the ocean brings an increased danger of oil spills. The Torrey Canyon, whose wreck severely damaged a portion of the English coastline, was a small supertanker with a capacity of only 35-million gallons of oil. These giants bring further problems. We must build deepwater ports to unload them as none of our present ports is deep enough.

The danger of spills and the increased handling of oil, offshore and at the coastline, threaten the economically and biologically important coastal fisheries and spawning grounds. The expected opening of the Atlantic Continental Shelf to drilling adds to this threat. The increase in oil-related activities in coastal regions, the building of ports, refineries, etc., also changes the character of these regions, increases population, brings cities, sewage, etc. All of these considerations must be a part of energy planning.

Nuclear Energy

In the 1970s we began real commercial use of a new form of energy, energy from the nucleus. Many planners are counting on nuclear reactors which use uranium for fuel to provide 30 or 40 percent of our electricity by 1985.

Nuclear energy may help solve some of our pollution problems, but it may give us new ones. It could relieve some of the air pollution problems presented by the fossil fuels. Since a conventional nuclear plant using 130 tons of uranium per year will produce the same amount of energy as a coal-fired plant using 2 million tons of coal per year, we can expect to relieve some of the worries over strip mining also. All energy conversions pollute, we can take this as a law of nature, and nuclear energy presents its own special hazards.

Radioactive pollution: Since man-made radioactivity is a relatively new hazard, there is considerable uncertainty and controversy over its effects. There is no question, however, that radiation is harmful. In large doses it can cause death, in smaller doses it can cause cancer and leukemia and can, through the damage to genes, produce defects in future generations. There is also no question that radioactive materials are produced in reactors; the debris of the fissioned uranium nucleus is intensely radioactive. What is in doubt is how much of this radioactive pollution will become a part of the environment and what effect it will have on humans.

The environment is exposed at three points in the nuclear fuel cycle: at the reactor, at the fuel processing and reprocessing plants, and at the waste disposal site. Great care is taken to contain the radioactive effluents at the plant, but small amounts do get into the air and water. The present regulations are not as strict at fuel processing and reprocessing plants and higher levels have been measured at some of them. Waste storage is still a developing technology and it is not clear what the final solution of this problem will be. What is certain is that some mechanism for long-time security will have to be established, for these wastes remain dangerous for hundreds of years.

There is considerable controversy over the possible effects of low levels of radiation exposure. We can summarize the middle-of-the-road scientific opinion in the following way. Exposure to radiation from nuclear reactors will be much less at present and in the near future than exposure to natural sources of radiation. There will be some damage, however, hidden in the greater damage from natural exposure. Some people may die and some genetic damage is being done which can be statistically blamed on reactors (just as some damage is done by the *sulfur oxides formed* by burning coal). We cannot, however, point to specific instances.

If we turn to the "breeder reactors" for power, we bring a more dangerous radioactive hazard, plutonium, into the picture. It is one of the most potent radioactive poisons known to man; it is longer-lived (it will be around for thousands of years), and its biological activity is even less well understood than that of the other radioactive products. We must prepare to receive it into our environment with extreme care.

Reactor accidents: A second, and also new, hazard that will accompany our turn to the nucleus for power is the danger of catastrophic accident. Nuclear plants are designed with two or three overlapping safety systems and their record so far has been excellent. No one has been killed in an accident at a commercial facility. The same enormous release of energy, however, which makes the nuclear reactor a favored source of power also makes it potentially dangerous. If an explosion were to spread the radioactive contents of the reactor over the surrounding countryside, it would be disastrous.

Trying to estimate the chances of such an accident is a little like trying to estimate the probability of being hit by a falling meteor (and we have better data on meteors). Nonetheless, the presently quoted odds of 1 in 10,000 or even 1 in 1,000,000 reactor-years* are not completely comforting as we face a future with 500 or 1,000 reactors in operation.

Hijacking and bombs: As long as we stick to the conventional, so-called light-water reactors for our energy, we can keep the question of bombs and reactors separate. These reactors cannot accidently explode like a nuclear bomb (the explosion we referred to earlier would be a steam explosion or a small scale "nuclear fizzle"). To make a bomb with stolen fuel or fuel products is also impossible; it takes expensive and sophisticated equipment to separate out the pure bomb material. As we mentioned earlier, however, with the breeder reactor we are in a different and much more dangerous ballgame.

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*A reactor-year is one year's operation of a reactor, 100 reactors operating for two years, for instance, equals 200 reactor years.

The fuel that the breeder makes is plutonium which, because it is chemically different from the uranium it is mixed with, can be more easily separated. Our production of this material is expected to rise from pounds to tons per year as we enter the era of the breeder and we will have to transport more and more of this potential bomb material across our country. There is at present much discussion and deep concern over the threat of hijacking, sabotage, and the nuclear blackmail that we are opening the world to. We must provide the plans for plutonium security now. It must be an error-free system, for mistakes can be the size of Hiroshima.

The Other Threads

We have spent the last sections discussing possible effects of the production, transportation, and consumption of energy on ourselves and on the biological environment we are a part of. The threads of the energy web extend as well into our social and economic systems. We mention some of these threads below; in later chapters we will follow them in greater detail into these other parts of our total "environment."

Energy and Economic Growth

Energy is the driving power for civilization. It is both a raw material and a "laborer" in industry. It is necessary for our comfort, communication, and transportation. The industrialized countries are the large consumers of energy; high standards of living mean high per capita consumption.

Energy consumption is correlated with the GNP, that indicator of economic strength. We saw evidence of a negative sort in the drop of the GNP during the oil embargo. Positive evidence is provided by the fact that almost all countries which have high per capita GNPs also have high per capita energy consumption. (We will look at this correlation in detail in Chapter 5.)

In this country, the record over the past few decades of the relation between the GNP and the consumption of energy is an interesting one. The ratio of energy consumed per dollar of GNP has been decreasing, we have been getting more GNP dollars per unit of energy. In the late sixties, however, this decrease stopped and it may be that our long period of improving efficiency is over and additional GNP dollars will be won only by increasingly large amounts of energy.

Energy and employment: It is not unexpected from the relationship we just examined to find that energy is also strongly connected with employment. Again, the embargo results back up this conjecture. The links between energy and employment are multiple, however, and different messages are carried along them.

There is no question that direct links exist and that energy shortages in many industries mean job shortages. This is particularly true in industries in which energy is essentially a raw material; in refining and gasoline and fuel oil marketing, for instance, or in the primary metals or plastics industries. These latter are particularly sensitive to energy fluctuation since the raw materials come from coal, oil, or natural gas and energy from these same fuels is needed to create the products.

The energy industries, however, are not large employers, they are capital intensive rather than labor intensive. Most of the workers in this country are not directly affected by energy consumption. It seems quite clear that a reduction in consumption, which was accomplished by improving the efficiency of energy utilization, could occur without reducing employment.

Energy cost: The most striking economic signal we have received from energy has been its soaring cost. For the past two decades energy, in all its forms, has been a bargain compared to other consumer items. This has been particularly true of electrical energy, whose price (either in constant, uninflated dollars, or actual dollars) has dropped steadily since the 1930s. In 1971 this trend turned around and for the first time even the constant dollar cost of electricity began to rise. It is expected to rise from its average of 1.5 cents per kilowatt hour of 1970 to 1.8 cents per kilowatt hour (in 1968 dollars) by 1990. With inflation, the actual dollar cost may be as much as 7 cents per kilowatt hour.

The records of other energy forms are similar. The cost of a gallon of regular gasoline has gone from about 35 cents per gallon in 1972 to 55 cents in 1974, fuel oil from 19 cents a gallon in 1970 to 31 cents in 1974, natural gas from 90 cents a thousand cubic feet to 120 cents in the same three-year period. The price of coal has also increased, the TVA paid $4.60 a ton for utility coal in 1969 and $28 per ton in 1974.

We are paying more for energy for several reasons. Profits, especially in the oil industry (and especially to the Mideastern producers), have increased, labor costs have increased, and the cost of environmental protection is beginning to show up in a small way. Whatever the reasons, the energy bargain days are over, at least temporarily.

Energy and the poor: Rising energy prices are increasing the gap in energy use that exists between the well-to-do and poor. The well-to-do household (average income $24,500) uses twice as much energy as does the poor household (average income $2,500), but only 4 percent of the income in the well-to-do household is spent on energy as compared with 15 percent in the poor household. As always, rising prices place a heavier burden on the poor.

Energy and the food system: The total amount of energy used in the production, processing, and delivery of food is rising much more rapidly than the total energy contained in the food. It now takes about 10 to 15 Calories of largely fossil-fuel energy to get 1 Calorie of food energy from the farm to the table. The inefficiency of the American food system makes us question its growing role both as a supplier of hungry countries and as an example for emulation.

Energy in Foreign Affairs

The control of resources has always been a major factor in relations between countries. The shortage of oil and its pivotal role in industry and transportation have combined to make oil in particular and energy in general a major international policy issue.

The United States has been historically energy self-sufficient. It was an exporter through the first half of this century, selling raw materials and especially manufactured goods to the world. We began to import oil in significant amounts in the 1950s. It is no coincidence that by the late 1960s our balance of trade began to show a deficit. In 1970 our total deficit was $4.7 billion and $2.1 billion of this was from oil and gas purchases. (We actually imported $3.6-billion worth of energy that year, but exports of coal and of oil products produced $1.5 billion in revenues.)

The contribution of energy purchases to the trade deficit will certainly grow for several years: projections range between $9 and $13 billion by 1975 and between $8 billion (for the optimistic supply case) and $32 billion (for the pessimistic one) by 1985. We cannot say with any certainty what effects on our economy and on the world's economy these huge money shipments will cause.

Foreign policy: There is an immediately obvious effect, however, on foreign policy. The Arabian oil producers were able to use their control of oil to force changes in foreign policy statements, and to some extent, actions by much of the Western world. The United States and the Netherlands were among the few countries that resisted the embargo-backed demands. The control of such a vital international commodity by a narrowly-focused group of countries will cause much concern and call for delicate and enlightened negotiations during the next decade. The United States with its traditional support of Israel is in a particularly difficult position.

The industrially underdeveloped countries are even more vulnerable as most of them are also energy importers. The challenge to international policy goes beyond loans for oil purchases. It must also include loans of money and "know-how" to enable them to build up local sources of energy. Water, wind, and sun may be their energy of the future.

Summary

In this introductory chapter we have given a brief and largely qualitative picture of the energy web which laces together all parts of the biological, sociological, and economic environment. The existence of this web was brought home to many of us by the jangling it received from the oil embargo of winter and spring 1973-1974. From that experience, we were able to measure some of the relationships of energy to money, work, and play. The GNP declined by about $15 billion, 500,000 jobs were lost, and all prices increased.

We described in broad outline the input-output statistics of energy. The 19 quadrillion Calories of energy we used in 1973 were shared by industry (35 percent), transportation (25 percent), residences (24 percent), and commerce (10 percent). Six percent was used as raw materials. The input was 95 percent from the fossil fuels (oil 46 percent, natural gas 31 percent, and coal 18 percent). The rest came from hydropower (4 percent) and nuclear energy.

We pointed to the energy areas that have or are about to become critical ones: the importation of oil, the shortage of natural gas, and the growth problems in the electric utilities industry. We also summarized the present and future areas of environmental concern: air pollution, the competition for water use, land use and ocean use, and the new concerns growing from our increasing reliance on nuclear energy.

We finished with a glance at those strands in the web which cause energy decisions to interact with our economy and even our foreign policy.

Chapter 1 has been an introduction to a most complex issue. In it we have tried to show both the breadth and the depth of the energy web. We must now, to an extent, forget the whole and look at the interconnected parts which form it. In the next chapter we begin with the environment, that source and sink for energy which suffers at both ends of the energy flow.

CHAPTER 2
Energy Production and the Environment

Energy Production and the Environment

One of the most important lessons of ecology is that "everything is connected to everything else." Nowhere is this lesson more convincingly taught than in the overlap between the "Energy Crisis" and the "Environmental Crisis."

If we begin our study of crisis with energy, and worry about the inability of supply to meet demand, we are immediately told that obstruction by "environmentalists" has slowed down the construction of generating plants (coal burning as well as nuclear) as well as oil refineries. Pointed to are delay of the Alaskan pipeline, the moratorium on offshore oil production in the Pacific, and attempts to restrict strip mining for coal. We are also warned of the need for much more energy to repair past damage to the environment and to safeguard its future.

If we enter the question by way of the environment we come immediately to energy. Air pollution is, for the most part, a problem caused by energy consumption. Most of the harmful chemicals in smog come either from the fossil-fuel generating plants or the automobile. The production and transportation of energy are responsible for strip mining, oil spills, and the "aesthetic pollution" of transmission lines. Energy consumption also causes "heat pollution" of our rivers and of our cities' air and is behind the new threat of radioactive pollution.

Whatever our approach, whether environmental protection or energy consumption, it is clear that energy and environment cannot be studied separately. In the next three chapters we will look at several aspects of these complex interactions. Our focus in this chapter is on the environmental effects of "production" of energy, its extraction from primary sources.

First we look at the primary sources of energy: the fossil fuels, uranium, and the running water that turns turbines at our many hydroelectric plants. (We describe these sources and estimate their sizes, importance, and prospective lifetimes in Chapters 1, 2 and 4 of Volume II.) To begin, we look at coal, that old fuel which is regaining eminence.

The Environmental Costs of Coal Mining

After two decades of decline, the production of coal from this country's mines has begun to grow again. The 590,000,000 tons of coal mined in 1973 is expected to be 850,000,000 tons in 1980. The historical picture of coal mining, the miner with the light on his cap picking away at the wall of an underground mine, has changed drastically. Half of our coal still comes from underground mines; though practically none of it is mined by hand anymore. The other half is mined above ground by huge strip-mining shovels and "draglines." Whether drawn from deep mines or ripped from the surface, the extraction of coal often damages the countryside that contained it.

Strip Mining

Surface mining of coal has rapidly gained prominence in the past two decades. In 1950 a quarter of the total tonnage was produced by strip mining, in 1970 half came from surface mines. This method of mining will be important for several decades since about a third of the 390 billion tons of coal reserves (see Table 2-2, Volume II) can be mined from the surface.

Strip mining is simple in concept but it requires the use of some of the most impressively oversized equipment in existence. A huge shovel or "dragline" digs a long trench to get to the coal seam. Smaller shovels dig out the coal and load it into huge trucks for delivery either to a nearby "mine-mouth" generating plant or a railroad loading. The largest of these shovels, "Big Muskie," can dig 325 tons of soil in one bite, and trucks or earth movers capable of carrying 100-ton loads are in service.

Unreclaimed land that has been strip mined is a desolate sight indeed, and the careless mining practices of the past (and the inadequacy of regulation) have left us a legacy of hundreds of thousands of acres of such desolation. The effects of strip mining on the land depend somewhat on the topography, on whether it is flat or hilly. The basic disruption is similar to deep plowing. A long trench is dug and its coal removed, then a parallel trench dug and the "overburden" (the soil above the coal) is dumped into the old trench. On flat land this process produces long furrows of upturned earth. On mountain sides the cuts often circle the peaks with cliffs and "spoil banks" of piled earth. The mountain is peeled like an apple.

For both types of terrain, part of the resulting problem lies in the sterility of what is left. In the past the topsoil was usually buried under 50 or 100 feet of rock and sterile subsoil. If the stripped area is on a hill or mountainside, the problems are further complicated by erosion and landslides; there are no roots of trees or grasses left to give the soil stability. Without stability, even on flat land, wind and water move the residue in unwanted ways.

Rainfall not only causes erosion and fills nearby streams and lakes with silt but adds a further hazard. Coal is usually formed with considerable sulfur contamination (this is the source of some of the smog chemicals released in its burning). Water leaches out this sulfur and forms sulfuric acid which, if intense enough, can kill marine life in the streams it reaches and lessen or destroy the fertility of the land.

The approximately 5 billion tons of coal taken from surface mines between 1930 and 1971 resulted in about 1½ million acres of strip-mined land, according to the Bureau of Mines' latest summary.[1] If strip mining accounts for 60 percent of the 8.3 billion tons of coal expected to be mined between 1975 and 1985, we can anticipate another 1½ million acres to be added. This total of 3 million acres, or 4,700 square miles, is an area twice the size of the state of Delaware. At the time of the last survey, in 1971, about a third of the 1½ million acres were unreclaimed and many of the remaining acres were only partially reclaimed.

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[1] Bureau of Mines Information Circular #8642.

We cannot afford the pioneer luxury of leaving this land desolate. Fortunately, it appears that new state laws and tighter enforcement of existing laws have brought considerable improvement in the overall picture. Reclamation efforts (which we will discuss in a later section) have become both more sophisticated and more widespread. There is hope the 1½ million acres to be stripped in the next decade will be left in better shape.

Underground Mining

To first appearances underground mining is much less environmentally destructive than strip mining. It is messy, but so are many industries. The most obvious damage is from land subsidence, from mine cave-ins. Although most mining laws require that pillars, which sometimes amount to 50 percent of the coal, be left in place to hold up the roof; the mines cave in nonetheless. The Department of the Interior estimates that 8 million acres of land have been undermined by coal extraction and that 2 million acres have subsided. Most of this is in rural areas and creates problems of land usage. The 7 percent of subsidence under urban areas has caused more serious effects.

Mine acids, from deep mines, are also environmental threats. The most troublesome sources are abandoned mines below ground water levels; the leakage from deep and surface mines has contaminated more than 10,000 miles of rivers and streams in coal country. The Department of the Interior has estimated the cost of controlling acid mine drainage in the country at $6½ billion. Pennsylvania alone faces a $1 to $2-billion cost and has embarked on a $150-million 10-year plan to restore water quality.

The most serious damage to land and water from underground mining may also be behind us. Many state regulations have been toughened and the new Federal Water Quality Act can also be invoked to protect rivers and streams from acid drainage.

Waste Heaps and Fires

Forgotten by those who are unfamiliar with coal country are the fires that burn uncontrollably in many underground mines. Since 1949 a program of the U.S. Bureau of Mines has successfully brought 150 mine fires under control, but at last count 200 were still burning, damaging the surrounding area and consuming valuable resources.

Coal mining is the third ranking industrial producer of mineral wastes, most of which come from washing the coal to remove impurities. There are at present more than 2 billion tons of this waste in unsightly banks, many of them near urban areas where wind and water erosion spread their dust. Some are on fire, adding to local air pollution.

The results are sometimes more immediately tragic. In 1972 a makeshift dam of coal waste gave way at Buffalo Creek, outside of Man, West Virginia; the disaster took 124 lives.

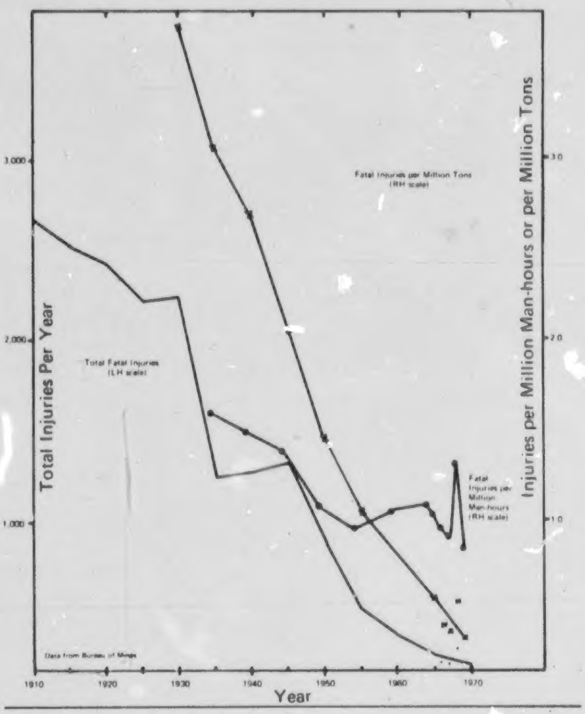
Much of this waste material is coal dust and one of the most satisfactory ways of disposing of it would be to burn it to create steam for electric power generation. There is some experimentation to this end.

Health Hazards

"Warning — Coal Mining May be Detrimental to Your Health," the sign should read. It is commonly considered to be the most dangerous industrial occupation. The data supporting this charge are shown in Figure 2-1. We show three curves: the total number of fatal injuries, fatalities per million tons of mined coal, and fatalities per million man-hours of mining. Both total fatal injuries and fatalities per million tons of mined coal have been reduced dramatically since the early part of this century. The total has gone from about 2,500 fatal injuries in 1920 to around 250 in 1970 and 132 in 1973. Fatal injuries per million tons of mined coal have dropped from almost four in 1935 to 0.4 in 1970 and 0.22 in 1973. The number of fatalities per man-hours worked, however, has declined more slowly. It was about 1.6 in 1935 and still around one in 1970. Due, one hopes, to the new Mine Health and Safety Act of 1970, this ratio dropped to 0.72 in 1971, to 0.56 in 1972 and was about 0.45 in 1973.

The decrease in the total number of deaths, and in deaths per million tons of coal mined, is a result of mechanization. The increase in the amount of coal mined at the surface has also contributed to the decrease in fatalities. In 1972, for instance, the number of

FIGURE 2-1
Coal Mining Injuries



fatalities per million man-hours in underground mines was 0.71 while it was 0.34 in strip mines.

The apparent greater danger of underground mining presents a difficult choice to land-use planners. How does land abuse balance against the dangers of underground mining? There is, however, some fairly convincing evidence that coal can be mined underground safely. There are coal companies engaged in underground mining whose statistics are better than some strip mining companies. Most of these exemplary companies are owned by the big steel producers. The nonfatal injury rate in U.S. Steel's predominately underground coal mining, for instance, was 5.3 per million man-hours in 1972 and 7.0 in 1973 as compared with 53.7 and 50.2 for the Peabody Coal Company, which produces 80 percent of its coal by strip mining. Even taking into account the fact that some of this difference may be due to different injury reporting practices, we can be encouraged by this comparison to believe that underground mining can be conducted safely. It should be. In the words attributed to Arnold Miller, President of the United Mine Workers Union. "If we can't mine coal safely, we won't mine it."

Black Lung: The most costly result of past coal mining practices is "Black Lung," a respiratory ailment caused by inhalation of coal dust. It is estimated that as many as 125,000 miners may have this life-shortening disease, which is similar to emphysema and is at least a contributing cause of 3,000 to 4,000 deaths per year. Unless great precaution is taken, mechanization, with its greater dust production, may increase its incidence.

Although the cost of death and disease cannot be measured in dollars, Black Lung does have a dollar cost that is already staggering. The 170,000 claims processed in 1970 (out of 250,000 filed) were settled for $151-million. The amount appropriated for 1972 was $385-million, and the final bill has been estimated at $8-billion. The early costs of Black Lung claims were borne by the taxpayer and represented a hidden subsidy for coal. As of January 1974, however, under the provisions of the Mine Health and Safety Act, the costs are borne by the coal company and are therefore added to the cost of coal. This should have a double benefit; the mining companies have a strong incentive to improve mining practices and the coal consumer, who pays directly for this additional cost, thus has added incentive to use coal as efficiently as possible.

Brightening the Picture

We have painted a rather dreary picture of the damage to land and living things incurred in coal mining. It is a true picture of the recent past but unfinished. The picture can be drawn much brighter. We have detailed these diseconomies of coal not to detract from its importance but because it *will* be so important in our near future. For at least another decade we will generate almost half of our electricity from coal-heated steam. It is important that the users of this electricity realize the real cost per kilowatt; more than that, as we have argued above, that they insist that all these costs of coal be added to the bill.

There is now some concrete evidence to support our hope that the picture is brightening. We have referred to new state and Federal regulations and to the drop in coal mine injuries following the new health and safety law. This law also may greatly reduce the future incidence of Black Lung. Measurements of dust levels in mines, taken by the Department of Interior's Mining Enforcement and Safety Administration, show that mine dust has been lowered to the specified levels.

Reclamation: The strip-mining picture has brightened considerably, also. Most strip-mined land can be reclaimed, if not to productivity at least to stability. The minimal steps are to regrade to the original contour and to reseed. This is important (but more complicated) on mountain and hillsides if landslides and erosion are to be prevented.

What determines the final condition of the land is often rainfall. In the Appalachians, the contour cuts must be dammed to prevent drainage of acid water, in the West, there is a danger of insufficient rainfall for reseeding and a worry that such rains as do occur may leach alkaline salts from the up-turned soil and create a problem soil which is too alkaline.

Reclamation is now a routine component of mining at most strip mines. The European practice of setting topsoil aside to put back on top after grading is coming more and more into practice. All states require grading and seeding and in many states the bonds posted by the coal companies are not released until vegetation has lasted through three growing seasons.

The brightening of the picture even extends to the statistics. According to the Bureau of Mines circular on strip mining we referred to earlier, 73,200 acres were strip mined for coal in 1971 and 94,600 acres were reclaimed. It appears that even some of strip mining's desolate legacy is being erased.

Uranium Mining

Uranium mining is carried out on a much smaller scale than coal mining: 6.5 million tons of this ore were mined in 1968, for instance, as compared with about 550 million tons of coal mined that year. Uranium is mined in both deep and surface mines, and its early history provides appalling examples of carelessness; radioactive waste water was dumped into rivers and homes were built on mine tailings. (The State of Colorado and the AEC have recently begun a program to remove the uranium waste used as fill dirt in several housing developments in that state.)

Uranium miners face the same dangers as coal miners, accidents, exposure to dust (which can cause respiratory problems similar to "Black Lung"), and fumes. The fact that the ore they seek is radioactive creates an additional hazard.

Uranium gives off a radioactive gas, radon, which, since it is heavier than air, concentrates in mine shafts. Breathing this air exposes sensitive lung tissue to radiation and the miner to the danger of lung cancer. A study of 3,400 uranium miners in 1968 found 70 cases of lung cancer, an incidence of this disease which is six times greater than in comparable groups. Since it takes 10 to 20 years, on the average, for lung cancer to develop, we are just beginning to see the first signs of what may be a serious human cost of production of this energy fuel.

Offshore and Arctic Wells

The search for oil and gas has taken man and his equipment deep into the continental United States. In the future it will take him into the relatively shallow waters of the continental shelf and under the Arctic ice where (as we describe in Chapter 2 of Volume II) more than half our yet-to-be-discovered oil is expected to lie hidden. In both cases he will expose a delicate environment to a new pollutant.

Oil Wells and the Ocean

We have produced oil from marine wells for some time, chiefly in the Gulf of Mexico and to a lesser extent on the Pacific Coast. Statistically, the record has been good. Of the more than 14,000 offshore wells drilled by 1970, only 25 have blown out of control. When this rare accident takes place, however, the results are dramatic and depressing. In the Santa Barbara spill of a few years ago, 50,000 barrels of oil caused considerable damage to the beaches and the shoreline life.

In addition to the rare "blowout," the development of offshore oil production also threatens the environment through leaks or breaks in the pipelines that carry oil to shore or through discharge of oily waste water into shore waters. A pipeline accident in the Gulf of Mexico in 1967 spilled 167,000 barrels of oil into the Gulf. Some 3,000 barrels of oily waste are also discharged annually.

It is estimated that worldwide offshore production of oil discharged 700,000 barrels of oil into the ocean in 1969 and that onshore refinery operations added another 2 million barrels.[2] In Table 3-1 we compare this pollution with other sources of the ocean's oil burden.

The environment at risk from these coastal operations is delicate and important. The deep ocean is a desert, as far as life per square mile is concerned. The richness we associate with it is confined to the shallow coastal areas, the bays, estuaries, and salt marshes. These are the incubators and the pantries of ocean life. We don't know very much about the long-term effects of oil on marine life. In large amounts it is toxic. There is growing evidence that some of the most toxic elements in oil are water soluble and are taken up and retained by ocean life. Since some of these are carcinogens (cancer causing), we may be threatening more than the ocean dwellers. We may find these carcinogens accumulating in the fish we eat.

Oil on Ice

The Arctic is similarly vulnerable. It is a harsh environment at best, its balance easily tipped against its inhabitants. It is also a region in which small changes can bring about large effects on our climate. For that reason alone we must allow change only when preceded by a thorough understanding of the consequences.

Drilling for oil and gas on United States land area has had minimal and localized effects. Small areas have been damaged by oil spills and the concentrations of men and machines. Oil spills in the Arctic, however, in particular those on the ice or ones that get under the ice, can have much more serious effects. A large spill would blacken the ice, making it more absorptive of the sun's radiation and causing it to warm and melt. Since open water is also more absorbent than ice, the warming process triggered by the spill could continue as the water absorbed radiation, was heated and melted more ice.

The Arctic region is the incubator of much of the Northern Hemisphere's weather and there is convincing evidence that changes in the ice cover there have been associated with large-scale climate change. A reduction of the Arctic ice cover from 1924 to 1944 was accompanied by changed wind paths and rainfall patterns. Summer droughts in the northern temperate zone became more frequent.

Since the U.S.S.R. and Canada, as well as the United States, have large-scale Arctic oil exploration efforts under way, the threat of oil on ice is a real one. It is important that we have a thorough understanding of the dangers and the technology to prevent them before we begin to handle large quantities of oil in the Arctic.

Oil Shale

We are beginning to look to the vast oil shale deposits of Colorado, Utah, and Wyoming for our future oil supplies. (The extent, nature, and means of exploiting these deposits are briefly discussed in Chapter 2, Volume II.) There are threats to the environment in this operation.

Mining the shale and extracting the oil from it by retorting (heating it to drive out the oil and gas) is the method nearest commercial viability. The mining will be accomplished both by strip or open pit mining and by underground mining. The impact of this mining threatens to be greater than that of the coal mining we have examined earlier. The energy content of an average ton of shale is only one-seventh that in a ton of coal; more of it must be mined to produce an equal amount of energy.

After the extraction of oil from the shale, there will be an enormous amount of spent shale to dispose of. The shale in the Piceane Creek Basin of Colorado (see Figure 2-2, Volume II), which is the region attracting the major interest at present, averages about 25 gallons of oil per ton of rock. Thus, for each barrel of oil (42 gallons) extracted, 1.7 tons of shale must be mined. After treatment this crushed shale will require disposal. Because of the crushing and the heating, the actual volume of rock to be disposed of will be greater than the space it occupied before mining.

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[2] "Man's Impact on the Global Environment" (Cambridge, Massachusetts: MIT Press, 1970), pg. 267.

The Green River region presents challenges similar to those faced in Western strip mining. Much of the area experiences low rainfall so that reclamation will be slow, the crushed rock will expose many unwanted chemicals to be leached out by such rain as does occur. The deep mining may change existing ground water flow patterns.

Some of the environmental impact of mining and exterior retorting of oil shale can be lessened if the technique of *in situ* production can be successfully developed. In this technique a region of shale is drilled and fractured either by hydraulic pressure or explosives. The shale is then set on fire and the fire sustained by compressed air. What burns are the volatile gases driven from the rock, the oil vaporizes and then condenses on cooler rock surfaces and collects at the bottom of the crushed region from which it can be recovered by additional wells. *In situ* production avoids the problems of waste rock disposal. It is not yet a viable commercial process and there are still questions to be answered about its deleterious environmental impact. Its effect on ground water supply and purity, for instance, needs more study. It will also be a relatively inefficient means of utilizing the oil shale.

The similarity with the Four Corners situation continues when aesthetic and recreational values are considered. Not only is the beauty of the mountainous area threatened but one of the largest herds of mule deer in North America winters in the million-acre Piceane Creak Basin where the shale development effort is now focused. There is serious concern over the effects of destroying their traditional habitat.

The emergence of a shale industry of the size targeted by present Department of Interior plans — 1,000,000 barrels of oil per day by 1985 — will not only require the mining and disposal of about 1,700,000 tons of shale per day but will also completely change the socio-economic characteristics of the region. The 150 present inhabitants will be augmented by a much larger work force to support the industry. Cities, roads, communication systems, schools, etc. will need construction. Water demand in this water-short region will increase.

The future of oil shale is very uncertain, especially so since the "Black Friday" decision of October 4, 1974. The production of oil from these rocks was expected to take its first giant step forward from the "Colony Development Operation," a pilot, 50,000 barrel-a-day processing plant that was to be built by a consortium of oil companies. On "Black Friday" the plans were called off.

One of the important factors was the inflation in construction costs. The 1973 estimate of plant-cost was $450 million, the latest estimate $800 million. The corresponding estimates of shale oil cost soared from $6 per barrel to $12 per barrel. Given the uncertainty of the final price of Mideastern oil, $6-barrel oil is worth a gamble but $12-oil is not.

The uncertainty of shale oil costs is accompanied by uncertainty over the net energy gain. There are two studies which claim that if the costs of mining, processing, transporting, etc. are taken into account and if the energy costs of the manufactured materials to be used by the shale industry are added, no net energy is gained in processing oil shale. This analysis is contradicted by Department of Interior studies that show output to input energy ratios as high as 10 to 1, but which do not apparently include manufacturing energy. The net energy question deserves a definitive answer before oil shale mining and processing, with its large environmental and sociological impact, are allowed to begin.

A program to obtain our needed energy from oil shale must be put in the same category of questionable solutions as was large-scale Western coal mining, offshore and Alaskan oil and gas drilling and the breeder reactor program. All of these carry as yet unmeasured environmental risks and should be entered into only after proper safeguards are established and only then when the need for this additional energy is clearly established.

These four issues (Western strip mining, offshore and Alaskan oil, the breeder reactor program, and oil shale) are among the most challenging ones which face the readers of this Source Book and their students. A fifth related and equally crucial issue should be added, large-scale importation of oil and gas, which raises questions concerning the effects of transporting and handling these fuels. We will discuss this issue in the following chapter. The answers cannot be based simply on environmental information, but must take into account the supply and demand information of Chapters 4 and 5 of Volume II, the alternative energy sources discussed in Chapters 6 and 7 of Volume II, and the social, economic, and political factors which are dealt with in the last two chapters of Volume I. These five issues have perhaps the highest priority of any discussed in the Source Book, but there are others of only slightly less importance and we continue with their review.

Dams and Reservoirs

Hydroelectric power produces only 15 percent or so of our electric power and is of major importance only in the West. The train of energy conversions here is a short one; the mechanical kinetic energy of water is transferred to a turbine and electric energy is produced by a generator. The environmental effects are correspondingly smaller but they are not nonexistent. The environmental impact which derives from tapping this source of energy differs from most of the others in that one can point to benefits other than the energy provided.

The creation of reservoirs, in fact, has counteracted some of our other activities (water pollution and algae stimulation from over-fertilization) which are destroying lakes. A reservoir provides recreational benefits, increases certain fish populations, causes local and often beneficial changes in ground water level and atmospheric moisture. Flood control is improved, a human benefit that may have deleterious effects on marine life, which counts on seasonal flooding for food and uses the flood plains for spawning and nursery areas.

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The effects of dams have not been adequately studied, and while we are probably nearing the end of the dam-building period in this country, there is much additional waterpower to be harnessed in the world (as we document in Chapter 2, Volume II). To the extent that we play a role in this activity elsewhere, we must remember the lesson in ecology taught by the Aswan Dam on the Nile. The ecological assessment was not done in advance of the engineering and as a result there are, in addition to electric power and irrigation, a ruined sardine fishery at the Nile's mouth and an epidemic of a waterborne parasite in the irrigated regions.

We must not forget, in these ecological evaluations of dams, their most obvious impact. Dams are most productive in deep canyons with swift streams. Such spots are usually among our most scenic ones. Glen Canyon in Utah is now Lake Powell. The Bureau of Reclamation preceded its advocacy of the Four Corners development with a proposal to build two dams in the Grand Canyon region. These were stopped by public outcry as has been the plan to dam Hells Canyon, the deepest gorge in North America. These are again examples of choices between energy and environment.

Pumped Storage

While it is likely that the drive to dam rivers is abating, much attention will have to be given in the next decade to the environmental effects of pumped storage facilities (a sketch of one such facility is provided in Figure 6-5, Volume II). All that is needed here is a source of water and a modest hill (200 feet or so high) to build a reservoir on. One of the bitterest confrontations between the environmental spokesmen and the energy producers, however, came over the plans of Consolidated Edison of New York to build a storage plant on Storm King Mountain on the Hudson River. Building a reservoir on that summit would have leveled it, flooded 240 acres of wilderness area, and destroyed (in the words of one of the opponents) "one of the grandest passages of river scenery in the world." The construction of Storm King has been held up for eight years and is still in doubt.

There is an additional, generally unremarked effect of pumped storage, especially near urban areas like New York City. The advantage of pumped storage is that it allows the baseload plants (the big fossil fuel or nuclear plants which run at a steady level of power production) to store energy during off-peak periods (generally nighttime) when demand is low. If the baseload plants are fossil fuel burning, however, this would mean a continued production of air pollution into the night skies. For this reason it is anticipated that pumped storage facilities will be built primarily in conjunction with nuclear baseload plants.

The Non-polluters of the Future

In most of this chapter we have painted a somewhat disturbing picture of the interaction between energy production and the environment. It is true that, as far as our present energy sources are concerned, we extract energy only at environmental cost. This general rule will probably always hold, it is a corollary of "you can't get something for nothing." As we look ahead to some of the energy sources of the future, however, we see the possibility at least of extracting energy with less environmental impact.

Solar Energy

In Chapter 7 of Volume II we investigate several suggestions for tapping the enormous flux of power that arrives each day from the sun. These schemes range from those which draw from secondhand solar sources — wind, water power, and photosynthesis — to those which convert the direct energy of sunlight. All of these methods of energy storage have some environmental impact. However, since these techniques involve the collection of energy rather than its extraction from some ecological niche, the environmental damage is generally less.

The most promising techniques for tapping the secondhand sources are those which involve the production of methane or the direct burning of organic material (organic waste is of particular interest). This conversion can be polluting. It is a potential source of particulate material and therefore must be controlled. Most organic material, however, does not contain sulfur and thus that problem is lessened. The use of organic waste as a fuel, while it may present some problems of air pollution, offers a solution to the equally troublesome problem of its disposal.

The other secondhand solar sources, wind and waterpower, should have only minimal impacts on the environment. We have already discussed dams and reservoirs. Wind power is, at present, largely an unknown quantity environmentally. As we mentioned earlier, a major effort to extract kinetic energy from the wind might change weather patterns, and a study of these effects must therefore be a part of the technological assessment of this form of energy conversion. A large system of windmills across the country would also have aesthetic drawbacks.

Solar energy farms: A scheme for collecting thermal energy in desert areas and converting it to electrical energy was described in Chapter 7, Volume II. Since large amounts of land will have to be covered with solar collectors, this has environmental impact. The estimated 10,000 square miles to produce half the 10 billion Mw-hr of electrical energy projected for the year 2000, however, is only 2 percent of the land we now use to grow food and will not be much more environmentally disturbing. Cattle, for instance, could graze among the collectors pictured in that description. In addition, as we explain in that chapter, the radiation balance of the desert is preserved.

Solar seapower: There is also reason to believe that collecting energy from the temperature difference between surface and deep seawater would have a minimal environmental impact. The energy available there is so vast that large amounts could be tapped without causing appreciable temperature changes.

In this last section we have contrasted the environmental impact of some future techniques of energy extraction with those that now provide primary energy. The contrast is encouraging. It appears that if we can successfully negotiate the dangerous times directly ahead of us, the next 20 years, more or less, and can turn to some of these new sources for energy, we can remove much of the threat that energy extraction now places on us and on our environment.

Summary

There are measurable environmental costs of extracting energy from primary sources. These are most obvious in the case of coal where our experience is most complete. The choice seems to be between strip mining, which has already overturned some 2,400 square miles of land leaving much of it ruined, and underground mining, which causes cave-ins and ruins streams with its acidic drainage. Coal mining, especially underground mining, also extracts a price from the miners. It is among the most dangerous occupations and injury and disease must be counted in coal's cost.

We also mentioned some recent statistics which suggest the coal mining picture is brightening. The regulation of strip mining has been tightened and the reclamation techniques have become more sophisticated. In 1971, in fact, more land was reclaimed than new land was stripped.

There has also been progress in mine safety and in prevention of Black Lung since the passage of the Mine Health and Safety Act. The Federal Water Quality Standards have brought about improvement in the acid water pollution of coal-country water.

In this chapter we also briefly listed the environmental cost of extracting energy in other forms. Several future sources carry warning signs. If we turn to the oil shales for energy, we will be entering a mining operation larger than the one for coal. Oil shale has only about one-seventh the energy per ton of coal and most of the shale becomes waste rock to be disposed of. Oil shale is also a prime example of the continuing problem of turning relatively wild areas into mining and producing sites.

In turning offshore and to the Arctic for oil we are threatening a much more delicate environment than did pumping oil from the soil of Texas, Louisiana, or California. The shallow coastal regions can be seriously damaged by oil and the Alaskan tundra is threatened by all the activity taking place on it. We mentioned in particular the chance that oil spills on the ice might bring changes in climate.

The purpose of this chapter is twofold: to inform readers of the various environmental costs of digging and drilling (and damming) for energy, and to enlist their aid in making sure that future energy demands are weighed against these costs.

CHAPTER 3

Energy Transport and the Environment

Energy Transport and the Environment

Energy, unlike money, draws no interest when it sits unused. To obtain value from it we must deliver it to a customer. In some cases, the means for delivery have important environmental effects.

Energy is shipped in several ways. Oil and gas travel by pipeline across this country and oil is moved in larger and larger quantity by tanker from foreign sources. Coal travels primarily by rail, electricity by wire. We discuss the relative dollar costs of these different methods of transport in Chapter 3, Volume II. Transportation also has its environmental costs.

Moving Oil

As the United States begins to deplete its own continental resources of oil and looks to Alaska and to the Middle East for supplementary supplies, a new class of environmental problems is opened. It is impossible, apparently, to transport these millions of barrels of oil per day without spilling some. And, as we have indicated in the previous chapter, oil does not mix well with water or ice.

Oil Spills

The Torrey Canyon disaster off the coast of England in 1968 dramatically brought to our attention the growing environmental hazard posed by ocean shipment of oil. It was the size of the disaster, not the occurrence, that made it noteworthy. The Torrey Canyon was one of the first "supertankers," the huge floating oil cans which have begun to dominate international oil transport.

The Torrey Canyon had a cargo of about 35 million gallons of crude oil of which some 29 million gallons were spilled. The cleanup bill totaled about $22 million. This ship, by today's standards, was a small supertanker. Its "deadweight tonnage" (DWT, the "deadweight" is the load in long tons — 2,240 lbs. — that can be carried) was about 100,000. The largest supertanker now in service (the Globtick Tokyo) has a DWT of 477,000 and a capacity of 180 million gallons of oil. Larger tankers are being built and tankers of 1,000,000 DWT are on the drawing boards.

The effects of the Torrey Canyon wreck are still apparent. Oil-covered beaches and the 70 to 100 thousand seabirds killed were the most visible results, but the detergent used to disperse the oil did even greater damage to eggs and larvae and other parts of the ecological web of sea life. Divers reported large kills of shellfish on the ocean bottom.

It seems to be only a matter of time before one of these larger tankers comes to grief. Already the 206,000 DWT Japanese-built Metula ran aground, in the Strait of Magellan on August 9, 1974, spilling about 15 million gallons of her cargo into Chilean waters. The remainder was pumped out before she broke up in rough seas.

The Metula accident was little noted in the press, although the oil slick covered 1,000 square miles of ocean and fouled 75 miles of coastline. What it reminds us of is that these ungainly, unseaworthy ships — too large for any of the canals — are taking the historic routes around Cape Horn and the Cape of Good Hope. They are thus sailing through some of the roughest seas that can be found. The difficulty of handling the cleanup operation also augurs poorly for the proposed Alaskan tanker route we shall mention later.

Other oil leaks: Accidents are the most dramatic causes of oil pollution but not the most important ones. An estimated 2.4 million tons of oil were spilled or dumped into the ocean by man's activities in 1969 (see Table 3-1) and accidental spills of all kinds — ship collisions, well blowouts, etc. — only contributed 200,000 tons, one-tenth of the total.

Half of the total was attributed to "normal ship operations." Since oil flows in one direction only, from source to consumer, and since the consuming countries have no bulk liquid to ship in return, most tankers return empty. In order to remain seaworthy they fill up with water as ballast. It is the dumping of this water, now mixed with oil, that is the major cause of ocean pollution. We have mentioned some of the other sources, spillage and discharges from onshore operations, for instance.

Oil is also a major pollutant in the nation's rivers and this oil makes its way to the ocean. Most of the oil in the rivers finds its way there from sewage — used crankcase oil is one of the major components. Some of it, however, is also there due to transportation accidents such as the one on the Mississippi in 1973; four barges carrying diesel oil struck a bridge and spilled 12,000 barrels of it into the river. The next day the oil slick covered 160 miles of the river.

Table 3-1 summarizes the most important sources of the ocean's oil pollution. The total is quite uncertain, most of these sources are quite difficult to judge and estimates of the total range from 1.8 million to 11 million tons. The amount contributed by natural seepage, for instance, is in considerable doubt.

Since all the man-made sources should contribute in rough proportion to the total amount of oil produced and shipped, oil pollution, without corrective measures, should grow with consumption, doubling every 10 years.

TABLE 3-1
Sources of Ocean Oil Pollution, 1969

	Thousands of Tons of Oil
Normal Ship Operations	1,100
Normal Offshore Production	110
Refinery Operations	330
Oil in Sewage and Rivers	660
Accidental Spills	220
Total Direct Input by Man	2,420
Natural Seepage (est.)	110
	2,530

Source: "Man's Impact on the Global Environment," Cambridge, Massachusetts: MIT Press, 1970, p267.

Reducing the input: There are ways to reduce oil pollution. Since the contribution from normal ship operations is such a large fraction of the total a new definition of "normalcy" seems to be needed. International efforts are now under way to make "load on top" operation standard procedure. Since oil floats on water it is possible to pump most of the relatively clean water ballast out from under the oil and then let the oil, with a little remaining water, settle in a "slop tank" at the bottom of the storage tanks. New oil is then loaded on top.

There have been other suggestions for reducing the oil in ballast, separate ballast tanks, rubber membranes to separate the oil and water, etc. There are also important procedures on shore, during loading and unloading, which could reduce oil spills. What is needed is a full recognition of the importance of keeping oil out of the seas.

Oil from Alaska

An important fraction of the oil we will be using in the late 1970s and the 1980s will be coming from Alaskan wells, shipped via the Trans-Alaskan Pipeline from the substantial reserves located in the North Slope oil fields near Prudhoe Bay, Alaska. This pipe, upon completion in the late 1970s, will carry 2 to 3 million barrels of oil per day to the Port of Valdez in Southern Alaska, where it will be loaded on tankers for shipment to West Coast refineries.

There will be two major points of environmental impact from the transport of this oil, the effects on the Alaskan ecosystem of the pipeline and the effects of tanker shipments at Valdez. We will briefly consider each of these.

The pipeline: The pipeline is being constructed of "48" pipe, 789 miles of it. The fact that this oil is to be shipped in the Arctic causes several unique difficulties. The oil will have to be heated (to about 140° F) in order to insure its flow. This hot oil causes some of the most serious difficulties.

The northern part of Alaska is covered by tundra, a thin layer of topsoil on a permanently frozen subsoil, called permafrost. The hot oil line, it is feared, will kill nearby vegetation and the strip of dead vegetation will no longer be able to hold the soil from slipping over the melted permafrost. A major soil slippage could break the pipe.

The tundra ecosystem is a very delicate one. Oil spillage could cause damage which might take decades to repair. Of equal concern is the damage which will be done by the construction work itself, such as the mining of sand and gravel for the pipeline and maintenance roads. This disturbed land will also be slow to heal.

The pipe may present a problem to the Alaskan caribou. This deer-like animal congregates in large herds on the northern tundra in the summer and migrates to the southern forests when cold weather comes. Their migration must cross the pipeline route. It is not known whether the pipe, plus the barren, muddy strip along it, will be a barrier to caribou migration. The fact that the pipeline will be raised on stilts for much of its length (in order to avoid the danger of slippage mentioned earlier) puts another barrier of uncertain importance in their path. The pipeline company is, of course, aware of these dangers and is committed to practices and construction that will not cause damage to this important species. We will not know the results, however, until the pipeline is completed.

The Alaskan pipeline is not a direct threat to man's health. It will not darken our skies or heat the water in our rivers or the air in our cities. Like the oil shale development in Colorado or the desert power plants in New Mexico, what it threatens is the nature of the land itself. The land the pipeline traverses is the largest wilderness area left in this country. It is threatened in many ways by the construction activity and by the roads which will open up the region to casual tourists. A break in the line could be disastrous. Such a break could, as we have said, be caused by slippage on the permafrost. The pipeline, for much of its length, is in country with a high incidence of earthquakes and one of these could also cause a break.

There is a shut-off system in the pipeline to take care of emergencies, of course. Thousands of gallons of oil could be spilled, however, before the pipe was closed and the broken system emptied. If this oil were spilled onto tundra the damage would at least be localized. Spilled into marsh land where ducks and geese migrate to hatch their young, or into the Gulkana River, an important spawning ground for salmon, the damage could be widespread.

We cannot yet say with precision what effect the pipeline will have on the Alaskan wilderness. We can say with certainty, however, that it will be changed.

Problems at the South End

The environmental problems posed by the pipeline do not end when the oil is delivered to Valdez. Valdez is located on Prince William Sound, a difficult port for any ship. Not only is it dotted by islands and rocks, but it is noted for fogs and violent storms. If past experience is any guide, it will be impossible to prevent some spillage in the transfer of oil from storage facilities to tankers at the port and equally impossible to prevent an occasional tanker accident on the trip south. The great number of tankers needed to keep the oil moving (five "Torrey Canyons" every two days) will add to the risk of collision at the port itself.

As we have discussed in Chapter 2 of this volume, oil spills in the Arctic are especially troublesome. They evaporate and disperse much more slowly there and the Arctic marine life takes longer to recover.

The Alaskan pipeline is one of the most controversial projects we have undertaken in this country as well as one of the most expensive ($2.8 billion was the 1973 estimate and $7.5 billion the present one). Its environmental impact was the subject of an extensive study by the Department of the Interior. It was the subject of debate, lawsuits, and finally Congressional action. The major pressure which drove it through the barriers

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erected against it was this country's thirst for oil. Satisfying that thirst will bring profit to the consortium of oil companies building the pipeline, employment and economic gain to the citizens of Alaska, and tax revenue to the state. The costs will be more difficult to total but that total must be made to guide our further excursions into the wilderness in search of energy.

Transmission Lines and Other Pipelines

Supertankers and the Alaskan pipeline are new ways to transport energy and are adapted to oil, the item in most demand on the energy menu. Energy, however, has been routinely shipped around this country for some time, in other less newsworthy ways. We will catalog some of these below and summarize their environmental impacts.

Transmission Lines

Electricity is shipped by wire. It is transformed to very high voltages, 500,000 to 750,000 volts (to be compared with the 120 volts of home wiring). At these high voltages it is carried across the country on the familiar wirestrung towers.

The environmental impact of these lines is largely visual. They occupy a lot of space and interrupt a lot of scenery. In 1970 there were about 300,000 miles of these lines in the United States and their rights-of-way occupied 4 million acres of land, 6,250 square miles — a right-of-way 2 miles wide across the country. In 1990, according to projections by the Federal Power Commission, there will be 500,000 miles of line occupying 7 million acres of land.

As we go to higher and higher voltages a new question is raised. Will the large electric fields around these wires cause any health problems for people exposed to them? There is now enough evidence that there are effects to warrant a call for a thorough study before we commit ourselves to transmission voltages of 1,000,000 or even 1,500,000 volts.[1]

There is little hope that we will see less of these lines before the end of this century. Underground high voltage transmission is too expensive, too much energy is lost and there is little hope for breakthroughs of technology. "Superconducting cables," metal at near liquid helium temperatures, are far from realization and will have to carry enormous power loads (all of New York City, for instance) to be price competitive.

Sometime in the future we may turn to hydrogen as a preferred intermediate energy (see Chapter 7, Volume II for a description) and replace the shipment of electricity by wire with shipments of hydrogen by pipe. We look at that technique of energy transport at the end of this chapter.

Pipelines

Oil and gas are transported across the country by pipelines and gas is also distributed and delivered by pipe. Some 800,000 miles of gas pipe make up this system and much of it is under the metropolitan areas. That much of this pipe network is now old and in poor condition is evidenced by the gas leaks and the occasional explosions that are reported. If we ar[illegible] continue to depend on natural gas for another decade or two we must ask for a thorough study of the safety of the pipe system bringing it to us.

Shipping Nuclear Fuels and Waste

We have concerned ourselves so far in this chapter with the environmental impact of the shipment of energy; oil in tankers, oil and gas through pipelines, and electricity through wires. When we turn to consider transportation and the environment where nuclear energy is concerned, things are, as always, different. Nuclear fuel — uranium ore for the present — is so concentrated that massive shipments are not what is of concern. Fuel deliveries to a 1,000 Mw nuclear plant, for instance, might involve 3,000 to 4,000 railroad cars during a year while shipment of fuel to a coal burning plant would need 25,000 carloads.

Transportation of nuclear materials has the possibility of environmental impact in two different ways, in the return of radioactive debris to the fuel reprocessing plant, and in the transport of materials which could be used to construct nuclear weapons. Since we are still at the beginning of the nuclear age and these problems are still largely before us, it is well to examine them now and to foresee, if possible, any policies which might lessen their impact.

Transporting Nuclear Waste

Nuclear fuel in its present form is not a particularly dangerous material. It is weakly radioactive and chemically more or less inert. The danger is on the return trip.

As we describe in Technical Appendix 6, only a small percentage of the uranium in a fuel rod within the reactor actually undergoes fission. After six months or a year, however, the combination of fission and the changes which have occurred in the fuel rod during its intense neutron bombardment make it necessary to return the rod for "fuel reprocessing." This is a recycling operation during which the fissionable uranium is recovered along with plutonium, a useful nuclear fuel formed by neutron bombardment of the non-fissioning uranium.

When these spent fuel assemblies are first removed from a reactor they are intensely radioactive and are stored underwater for several months to allow the most intense components to die out. After this initial cooling-off period the fuel assemblies are then shipped in massive containers to the reprocessing plants. Present containers (which carry one assembly) weigh 30-35 tons; one is about a truckload.

The shipment of these radioactive materials has not been a cause for concern to date. There have been instances of misrouted shipments and there was apparently a radioactive shipment (not material from reactors, however) on a plane hijacked to Cuba, but the record shows no serious losses or accidents.

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[1] "Pollution by Electrical Transmission Lines," L.B. Young and H.P. Young, *The Bulletin of the Atomic Scientists*, 30, 34-38, December 1974.

Concern remains, however, fed by the magnitude of the potential harm that could be caused by spillage of this material and by the rapidly increasing amount of material which will need shipment as the nuclear reactor becomes a major part of our energy system. If the radioactive debris within the shipping container were spread by a train or truck wreck it could contaminate a large area. A spill into a water supply would be particularly catastrophic. The containers, however, are built to stand quite a wreck and have already remained unbroken through a train derailment.

Not only is it necessary to carry fuel assemblies back and forth from the plant, but there are large amounts of low-level wastes to be gotten rid of. The AEC[2] estimated that one 1,000 Mw reactor requires 80 fuel shipments and 65 shipments of low-level waste per year. Thus in 1974 there were about 2,000 fuel shipments and 1,625 shipments of low-level waste in the country. This will rise to 10,400 fuel shipments and 8,450 low-level waste shipments per year by 1980 — 52 shipments per day as compared with 4 shipments per day in 1974.

Hijacking and Nuclear Blackmail

The increased traffic in nuclear material causes the concern we have just described: that an accident might spill dangerous radioactivity. There are other worries.

In this day of hijackers and terrorists the radioactive waste could be deliberately stolen and used as a threat or a weapon. As far as present reactors are concerned, this is unlikely for two reasons: the spent fuel elements are extremely dangerous to handle, and stored as they are in massive containers, they are difficult to move. Unfortunately, as the dependence on nuclear energy grows, the trucks and trains will be carrying a much more valuable target for hijackers and terrorists — the raw material for nuclear bombs.

To develop the first "Atomic Bomb" the United States spent several million dollars on the so-called Manhattan Project which culminated with the successful Trinity test near Alamogordo, New Mexico, in 1945. The recipe for nuclear weapons remains a carefully guarded secret, but the test itself revealed the most important part of the secret, that the nuclear explosive works.

Since that time many countries have developed nuclear fission weapons, but the task of constructing a bomb still seems to most of us one which needs a national effort to succeed. We have been spared the do-it-yourself atomic bomb maker.

If, however, we look at all the skills, materials, and equipment needed to build a bomb, we see, in fact, that only the preparation of the bomb raw material is extremely sophisticated. The rest of the steps are within capability of many technically trained people.

A nuclear weapon consists of a certain amount of fissionable material, a "critical mass." When a critical mass of fissionable material is assembled it will explode. The trick, therefore, is to build a weapon in which the fissionable material is stored in pieces smaller than this critical mass and then to bring them all together with some triggering explosion. A simple way is to have two subcritical masses at opposite ends of a pipe and use explosives to ram them together.

The size of the critical mass depends on the type of material and its purity. There are three kinds of fissionable materials now in use, uranium 235* (the rare form of uranium which makes up only 0.7 percent of ordinary uranium ore), and the two man-made forms, plutonium 239 and uranium 233.

Uranium 235 is the fuel for present-day reactors and is therefore contained in fuel assemblies shipped to the reactors and in the spent fuel assemblies carried from them. In neither form, however, is it usable as bomb material, it is mixed with the much more abundant and chemically identical uranium 238 whose presence keeps the explosive "chain reaction" from taking place. On the return trip it is highly radioactive.

In the spent fuel, however, there are appreciable quantities of plutonium 239 produced from the uranium 238 by neutrons in the reactor. At the fuel reprocessing plant this plutonium is separated out and preserved. It is a valuable reactor fuel itself.

Since plutonium is chemically different from the uranium and the contaminants in the spent fuel, its separation is relatively easy and almost pure plutonium is produced. It is not pure plutonium 239, however. It is mixed with a sister product, plutonium 240 which has different nuclear properties and acts, in fact, as a "poison" to the chain reaction. Even with the 10 to 20 percent plutonium 240 typical of today's reactor fuel, however, this recovered plutonium can be used to make a bomb. The critical mass (if surrounded by a copper or steel neutron reflector) would be about 8 kilograms (18 pounds).[3]

At present the relatively small amount of this potential bomb material produced so far is stored at the reprocessing plants and is relatively secure. This security is threatened by several coming changes in the nuclear energy picture. The first of these is the policy of plutonium recycling; plutonium is to be added to uranium 235 in fuel elements and sent back to the reactors. It is thus exposed to theft during transit.

The major worry over nuclear theft, however, comes with the breeder reactors scheduled to begin operation in the 1980s. There are two types of breeders, the Liquid Metal Fast Breeder Reactor (LMFBR), which will produce plutonium 239 from uranium 238, and the High Temperature Gas Reactor (HTGR), which will produce uranium 233 from another nuclear material, thorium 232. Uranium 233 can also be used to make a bomb although it typically has a contaminant which gives off a penetrating radiation and this makes it dangerous to work with and less attractive to the bomb maker. Its critical mass is somewhere between 11 and 25 kilograms (24 to 55 pounds) depending on the reflector used.

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[2] We will in this chapter refer to the AEC, although that agency was abolished on January 19, 1975. Its research and development activities will be carried on by the Energy Research and Development Administration (ERDA) and its regulatory responsibilities by the Nuclear Regulatory Commission (NRC).

*The number identifies the isotope, the form of the nucleus. It is the total number of protons and neutrons in the nucleus. Isotopes are further described in Technical Appendix 6.

[3] "Nuclear Theft: Risks and Safeguards," Willrich and Taylor (Cambridge, Massachusetts, Ballinger Publishing Company) 1974 p12.

Plutonium 239 and uranium 233 appear at different points in the nuclear fuel cycle as different compounds, sometimes combined with oxygen, for instance, but their separation is not very difficult. The oxides also can be used as bomb material.

The important and worrisome point of the study[4] from which we drew the preceding data is that it does not take a lot of this material, expensive equipment or sophisticated technique, to make a crude bomb. It is therefore important to see what quantities of these raw materials are being produced. We summarize in Table 3-2 the production of plutonium 239 or uranium 233 by the present-day Light Water Reactors (LWR) with and without plutonium recycling and by the breeders. We see that each reactor produces enough raw material for several bombs, 26 plutonium bombs per year from the LWR, 37 from the LMFBR, etc.

These are the production rates of single reactors. The cumulative production is much more disturbing in its implications. This same study estimates that by 1980, 26,000 kilograms (almost 29 tons) of plutonium 239 will be extracted each year, enough for more than 3,000 bombs.

Security

The raw material for bombs will be available in quantity in the 1980s and will be vulnerable to possible hijacking during storage and shipment. It could also conceivably be stolen in small amounts at the reprocessing plant itself. Plutonium's value of $10,000 per kilogram makes it attractive and, of course, it will take on greater value to a group (or a country) attempting nuclear blackmail. Its great value, of course, also makes it doubly worthwhile to safeguard.

The danger has been recognized by the AEC and plans to increase security measures are being developed. The danger is so great that the cure may also be damaging. The establishment of a "National Security Force" for its protection is one suggestion receiving serious attention. It would be ironic, to say the least, if the generation of electricity with nuclear energy would force us to accept even this variation of a national police force we have so long resisted.

The dangers of theft and the lesser worries over nuclear waste transport are among the arguments for "Nuclear Parks": groupings of reactors, reprocessing and fuel fabrication plants and industries to use the electricity. This grouping would reduce transport miles and allow centralized security. However, they would have other environmental problems to deal with; waste heat disposal, for instance. They would also require a restructuring of our utility system.

The threat of the theft of bomb materials increases each year as production of these fissionable materials is increased. A bomb constructed from these materials would not have the sophisticated power of destruction of the bombs produced for military use, it might fizzle out at only a few hundred tons of TNT equivalence rather than kilotons. The damage that such a "fizzle" could do in a city, however, beggars description. We must add this danger to the cost of nuclear-generated electricity and satisfy ourselves that it is not too high a price to pay for energy from this source.

TABLE 3-2

Production of Fissionable Material in a 1,000 Mw Reactor

Reactor Type	LWR	LWR (Pu Recycle)	LMFBR	HTGR
Pu 239 (kg)	210	50*	300*	
U 233 (kg)				150-230

Source: **Nuclear Theft: Risks and Safeguards** Mason Willrich and Theodore B. Taylor (Cambridge, Massachusetts: Ballinger, 1974) p. 12.

*Net production, input minus output.

Future Problems

We have just described a growing problem of energy transport. There are others, not so dramatic, that will also have to be faced.

Deep Ocean Ports

Earlier in this chapter we described the supertankers which will haul more and more oil to us from the Middle East. These huge ships are not only big, they lie deep in the water. By 1972, there were 237 supertankers of greater than 200,000 DWT in service and ships of 400,000 to 500,000 DWT on order. A ship of 250,000 to 300,000 DWT draws 65 to 77 feet of water; a 500,000 DWT tanker greater than 90 feet. There are no United States ports that can receive these tankers. Long Beach and Los Angeles can handle 100,000 DWT ships; the limit at New York, Philadelphia, and Baltimore is 55,000 DWT.

A proposed solution is to build deep water ports several miles offshore where the ships can unload and then pipe the oil ashore. The environmental threat here has been described, oil spills in transfer, pipeline breaks, etc. The industrialization of the shore area by refineries and associated industry must also be considered. It is clear that the overall environmental impact of each of these ports must be carefully considered and weighed not only against our need for oil but also against the alternate sources and forms of energy.

Refrigerated Tankers

As our demand for natural gas exceeds our domestic supply, we are turning to foreign sources. The Texas El Paso Gas Company has signed a long-term contract with Algeria to buy liquified natural gas (LNG). There are also small spot shipments of LNG arriving at East Coast ports.

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[4] Ibid.

To ship gas, it is first liquified at −260°F and then shipped in refrigerated tankers. These tankers may contain up to 1 billion cubic feet of gas and their arrival in crowded port cities is a cause for concern. If a tanker should break up, the holocaust would be impressive. There is at present little information as to the safety of this form of energy shipment. There was a LNG disaster in Cleveland in 1944 when a tank exploded. The LNG got into the sewer system causing fires, explosions, and the death of 133 people.

LNG is dangerous even unexploded. At the lowered temperature it is heavier than air and heated from the ground it could flow as a dense mass for some distance. A billion cubic feet could form a cloud large enough to asphyxiate the inhabitants of a good-sized city. It would seem that the plans to increase the delivery of LNG to port cities, to bring tankers into the narrow confines of New York, for instance, would call for a carefully prepared "Environmental Impact Statement" but so far such a statement has not been prepared. We cannot, however, feel very comfortable until we are told what the dangers are and what security measures are needed.

Shipping Hydrogen

Somewhat further in the future is the prospect of turning to hydrogen as an intermediate form of energy. We discuss the advantages of hydrogen for storing and transporting energy in Chapter 6, Volume II.

At first glance it would seem that a gas like hydrogen would be an ideal fuel in a country already set up to distribute and utilize a gaseous fuel. Hydrogen, however, is very different from methane, the major component of natural gas. The hydrogen molecule, H_2, is much smaller and lighter than methane, CH_4. Because of this it is very difficult to control, it will leak easily through valves which would hold methane. It has the additional troublesome property of easily diffusing into metals, some steels, for instance, and in doing so renders them very brittle and easy to break. Use in our present pipeline distribution may take modification of valves and the removal of easily affected metals. The cast-iron pipes themselves, however, are thought to be satisfactory. We are thus a long step toward the possibility of a hydrogen distribution system.

Hydrogen is also potentially dangerous because when mixed with air it can explode. We have, however, a fairly long history of dealing with explosive fuels, methane and gasoline, for example. The care that its explosive properties will require will be in large part balanced by the innocuous nature of the combustion product, H_2O — water. The fact that hydrogen is light will be an advantage if it leaks or is accidentally spilled. It will quietly disperse and thus there will not be a danger from asphyxiation as there is with methane, for instance. At this stage the environmental problems of shipping and storing hydrogen are overshadowed by the economic problem of producing it cheaply. If the economic problem is solved, the physical one no doubt will be also.

Summary

In this chapter we have looked at the environmental costs of energy transport. The major concerns focus on the transport of oil and of nuclear materials.

Oil transportation has environmental impact in several ways. The most dramatic is through the danger of massive oil spills from the large tankers. These supertankers now carry hundreds of millions of gallons of oil as contrasted with the 29 million gallons spilled from the Torrey Canyon off the coast of England several years ago. As our importation of oil increases we will need the equivalent of three or four of these tankers per day unloading at our ports.

Oil tanker spills are the most dramatic, but the dumping of oily ballast water in routine operations causes five times the contamination of all oil accidents combined. If we are to preserve our vulnerable shallow coastal waters, we must find ways to cut down the spillage from all forms of oil transportation near our shorelines.

If spills are the most dramatic danger, the transportation of oil across Alaska by pipeline has been the most politically sensitive one. The TransAlaskan pipeline, now under construction, will carry 2 or 3 million barrels of oil per day from the rich North Slope oil fields to the southern port of Valdez. The effect of the heated pipeline on the delicate tundra with its underlying permafrost is a cause of concern as is the danger of breakage from earthquakes. The pipeline also cuts across the migration paths of the caribou and its effect on them will bear watching.

Transportation of nuclear materials is increasing rapidly. There were almost 4,000 shipments of fuel and waste materials within this country in 1974 and the number grows with the growth of the nuclear industry. While great precautions have been taken to keep the materials safely encased, the results of spillage are sufficiently serious to warrant continual surveillance.

The growing role of plutonium as a nuclear fuel introduces a new worry. This material is being shipped and stored in a form from which nuclear bombs could be constructed. Since even a crude bomb of 40 or 50 pounds could do enormous damage and since plutonium production by the end of this decade will be measured in tons-per-year (28 tons per year in 1980), we must develop a much more sophisticated security system than we have at present if we are to make major fuel use of this material.

These hazards of the transport of oil and nuclear materials are joined by the land use problems of transmission lines and the worry over the thousands of miles of gas pipe under our cities.

A working energy policy for the future must weigh the environmental costs of energy transportation along with other environmental effects and against the end uses of that energy.

CHAPTER 4

The Environment and Energy Consumption

The Environment and Energy Consumption

In the last two chapters we may have given energy a bad name by concentrating on the environmental effects of producing it in its various forms and delivering it to consumers. This chapter will continue that unflattering association of energy with environmental damage. We will now look at what happens at the end of the flow pattern. It is here, of course, that we use energy to our great benefit, to warm our homes and offices, provide transportation, and power the many engines and processes of industry. It is also here, at the consuming end, that we see, smell, and feel some of energy's most obvious environmental impacts.

We can gain much insight into the nature of consumption-related environmental problems by looking at the way we convert energy to our use. Most of our energy, 95 percent of it in 1973, comes from the fossil fuels. To convert their stored energy to our use we burn them. In burning we produce smoke and other less visible gases, and we produce heat. Air pollution and thermal (heat) pollution are, therefore, the major types of pollution we will find.

Although its present percentage share of the energy market (1 percent in 1973) does not warrant much consideration, the future prospects of nuclear energy require that we must also look at the new forms of pollution that it will introduce. And we must, for completeness, look ahead to some of the other hazards that may accompany the nuclear generation of electricity.

We will first look at that form of pollution that is before our noses, so to speak.

Air Pollution: Causes and Effects

The evidence for the existence of air pollution is not hard to come by, it is all around us. It is a more subtle observation to realize that this pollution is costing us money for much of the damage to places, plants, and people is indirect. In a recent estimate by the Environmental Protection Agency, the total bill for air pollution for 1968 was set at $16.2 billion, about $80 for every person in the country.

A partial breakdown of these costs included:

$6.1	billion for health effects
$4.8	billion for effects on materials (rust, corrosion, damage to fabrics, cost of protective coatings, etc.)
$5.2	billion for damage to residential property (including reduction in value)
$120	million for damage to commercial crops

There are other costs: damage to art, the aesthetic and psychological costs of dirty living and working areas, the damage to residential flowers and shrubs, for instance. It is difficult to put a dollar sign on these costs, and it is difficult to correctly price death, disease, and discomfort; but these all are costs that must be weighed into the balance.

What is air pollution? What are the damage-causing agents, where do they come from, how do they get into the air, what happens to them there, and what do they do to the world beneath them when they come back to it? We turn next to these questions.

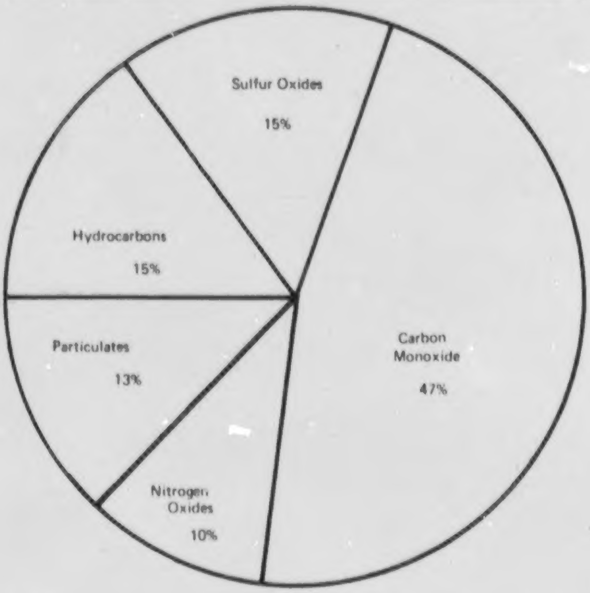
The five pollutants and their chemical shorthand symbols are: *carbon monoxide* (CO), the *nitrogen oxides* (there are several and we will refer to them all as NO_x), the *particulates* (soot, tar, "fly ash" and other miscellaneous material; there is no appropriate chemical symbol), the *hydrocarbons* (HC), and the *sulfur oxides* (SO_x). The relative percentages of these pollutants in the total mass of pollutants is shown in Figure 4-1.

All five of these are combustion products. Carbon monoxide is formed when carbon is burned with insufficient oxygen. The hydrocarbons are also products of incomplete burning, but here the fuel is a hydrocarbon, a molecule made of carbon and hydrogen like those that make up gasoline and other petroleum products. CO and the HCs are, thus, products of inefficiency, for there is energy left in them which could be released by further combustion.

The nitrogen and sulfur oxides are products of more specific combustion situations. The NO_xs are formed whenever there is a hot fire in air. The type of fire is not important, all that is needed is that air reach a temperature of 1,000°F or so. At that temperature (or above), the oxygen and the nitrogen molecules of air (O_2 and N_2) are torn apart and the atoms combine to form NO, nitrite oxide. Others of this group are formed by adding on additional oxygen atoms.

The formation of sulfur oxide is even simpler to understand, it is a product of the oxidation (burning) of

FIGURE 4-1
Distribution of Emissions Species, Percentage by Weights



Source: "The Automobile and Air Pollution: A Program for Progress," Part II, U.S. Department of Commerce, December 1967.

sulfur. It is produced, therefore, whenever a sulfur-containing fuel is burned.

The particulates are the most visible of the pollutants for they make up smoke and soot. They are also, in part, products of inefficient burning, as some of them are unburned, heavy hydrocarbons (tar) and carbon (soot). The "fly ash," the fine particles of mineral impurities, is also an important particulant impurity.

There is a sixth air pollutant which is assuming an unwanted importance, lead released in the burning of leaded gasoline. We will look briefly at it in this chapter.

The Pollutors and Pollutants

From the brief description of the five air pollutants we have strong clues as to their sources. This evidence is confirmed by the pie diagrams of Figure 4-2 which show the percentage contribution of the various sources to the mass of each of the five. Transportation (and you can read this "the automobile") is the major source of CO (74 percent), HC (53 percent), and NO_x (47 percent). Stationery fuel combustion (the fossil fuel burning electric generating plants) is the major producer of SO_x (73 percent) and a close second in the production of NO_x (42 percent). Only in the production of particulates does a non-energy source, industry, take the lead.

A summary of the overall responsibility for all these air pollution products was provided by Figure 1-4. The dominance of energy conversions is clear. Transportation accounts for 42 percent of the total mass and the electric utilities 21 percent.

The type of pollution produced by the automobile and the power plants, the effects of these pollutants, and the means for their control differ. We will look at the distinctive smog produced by these two sources separately.

Fossil Fuels to Electricity

As we see from Figure 4-2, the fuel-burning power plants are a source of sulfur oxide, particulates, and nitrogen oxide. Major concern at the present is focused on SO_x. Most power plants now employ "electrostatic precipitators"* which remove the bulk of particulate matter from their exhaust. The NO_xs are not presently considered a power plant problem, although the continuing growth of these plants may soon cause us to worry about this pollutant also.

Smoke, SO_x, and high humidity (fog) are the ingredients of the "classical" smog which has been associated with the worst air pollution disasters: Donora, Pennsylvania in 1948, London in 1952, and New York in 1966. The most troublesome agent in the smog is sulfuric acid (H_2SO_4) which is formed by a reaction of SO_3 (sulfur trioxide) with water.

The fine aerosol (droplets in air) of sulfuric acid is responsible for much of the damage. It corrodes and dissolves metal, stone, fabrics, etc., and is particularly harmful to precision equipment. Sulfuric acid does not long remain in the atmosphere; in two days to a week it is usually brought down by rain. In the past few years measurements have shown that rain and, therefore, lakes and rivers have been becoming noticeably more acidic. This has been particularly troublesome in the Netherlands and Scandinavia and serious effects on fish life in some Norwegian streams and lakes have been reported.

Effects on humans: The effects of the sulfurous smog on humans are not completely cataloged. It produces irritation in the upper respiratory tract and in the lungs when carried there by particles of the proper size. One of its subtle effects is to increase the "airway resistance," that is, make it harder to breathe.

These effects on humans illustrate a property of air pollution called "synergy." The synergistic effects of an agent, of sulfuric acid for instance, are those that result from a combination of agents and factors operating together. As an example, sulfuric acid by itself is removed from air by the filtering action of the nasal passages. If it exists in combination with soot particles (as it does in smog), then it will form an absorbed layer on these small particles; and if some of them are small enough to get down to the lungs, then the sulfuric acid can do more serious damage. The increase in airway resistance can also produce synergistic effects. A healthy person is only a little bothered by this, but it may be fatal to someone with emphysema or a weak heart.

Because of this general, indirect relationship to death or disease, it is hard to make quantitative relationships between air pollution and health. One can rarely say, "This person died from air pollution." The evidence is usually of a statistical nature. Figure 4-3 is the classical example which shows that an increase in deaths (in London in 1952) followed closely after (and had generally the same shape as) the pollutant increase. There is similar evidence, for instance, that lung cancer is much higher (three times as high) in urban smokers than in non-urban smokers. There seems to be a synergistic relationship between smoking and air pollution in the production of lung cancer.

From such statistical studies we can lay blame for the worsening of a long list of respiratory and heart diseases on the sulfurous smog.

Clean and dirty fuels: The fuels can be ranked, as far as sulfur is concerned, from clean to dirty. Natural gas is the clean fuel; it has little sulfur in it, and that which is there is easily removed in normal cleaning operations. Oil can have sulfur contamination of from as high as 2 percent down to 0.5 percent. (It is believed that Alaskan oil will be low in sulfur.) Coal is the dirty fuel, ranging up to 7 percent sulfur. Coal burning plants produce 90 percent of the SO_x and the particulates produced in the generation of electricity.

Air quality standards in many urban areas require that fuels have less than 1 percent sulfur to be used. It has been sometimes difficult in the last few years to find fuel oil to meet that standard. Low-sulfur coal is in even

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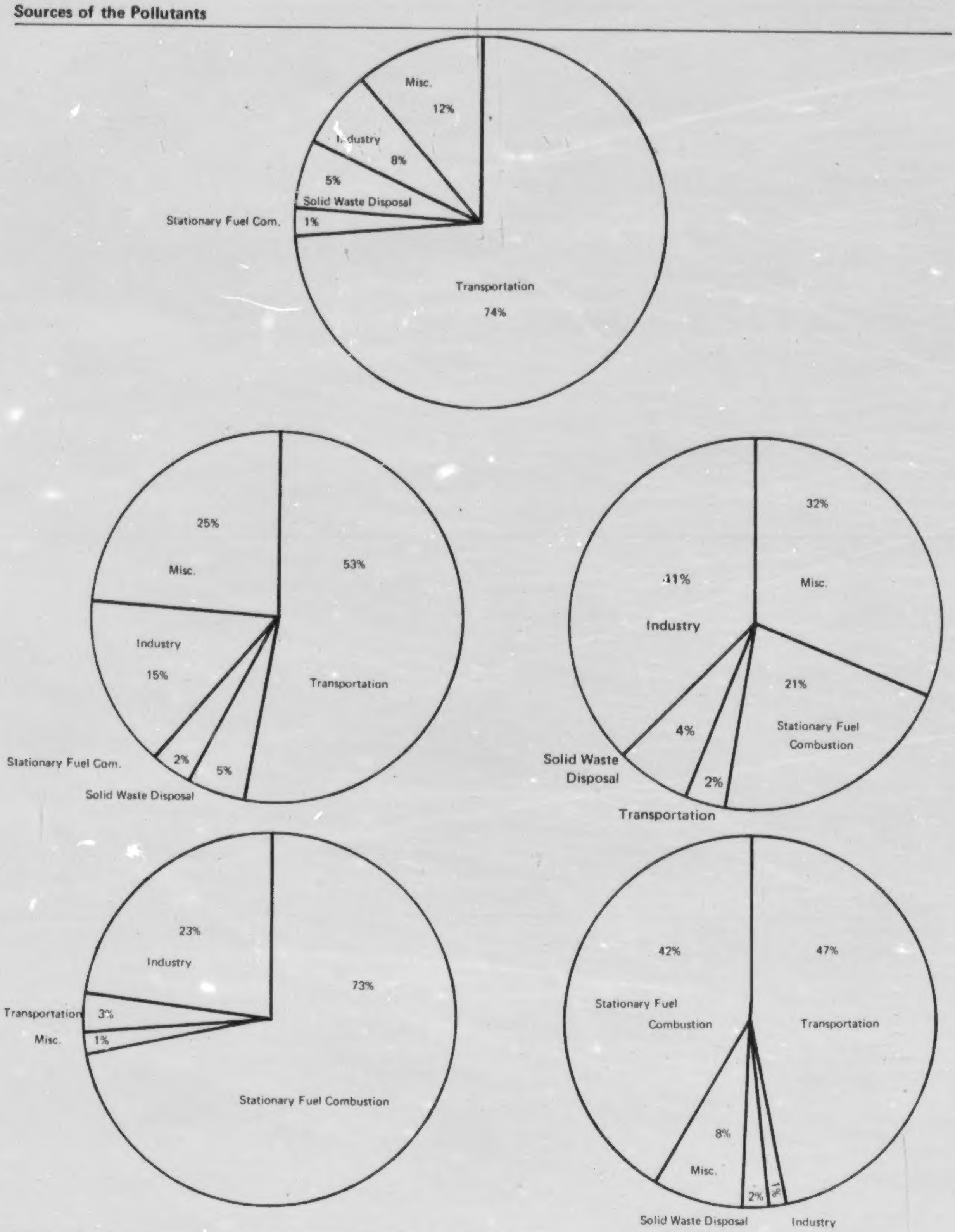
*The smoke particles are attracted to electrically charged plates much in the same way that hair or bits of paper are attracted to a charged comb. The accumulated particulates can then be washed away.

FIGURE 4-2
Sources of the Pollutants



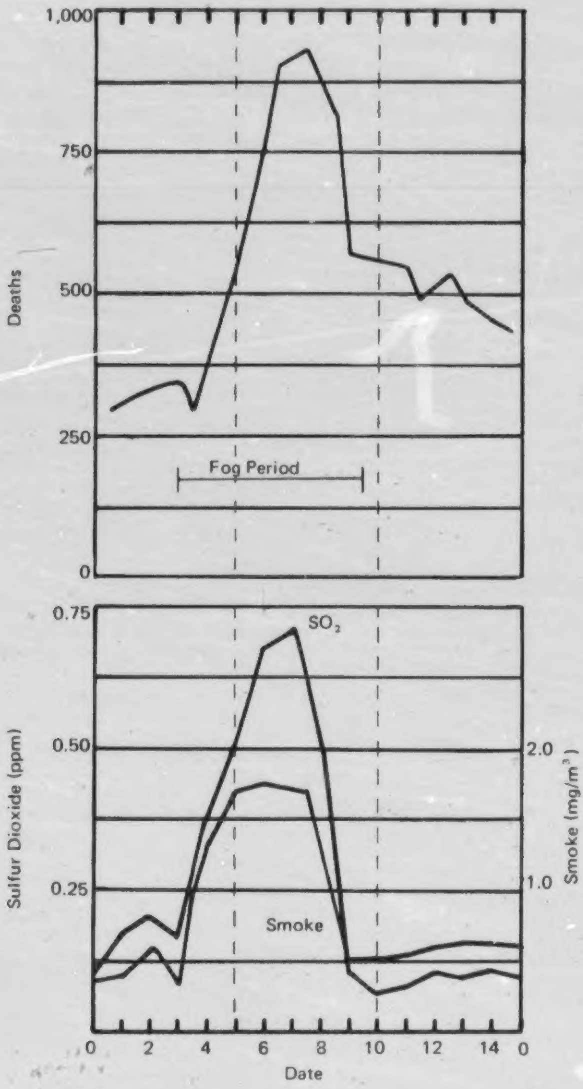
Source: "The Automobile and Air Pollution: A Program for Progress," Part II, U.S. Department of Commerce, December 1967.

shorter supply, particularly near the Eastern cities. The generally low sulfur content is part of the attraction of the Western coals.

Technology to the rescue: The cheapest and most straightforward way to reduce the SO_x in our air is to burn clean fuels, but the clean fuels are in shortest supply. The present approach is to remove the sulfur. Nature, however, shows her perversity here; not only will the "electrostatic precipitators," which are so effective on soot particles, not remove SO_x, but, in fact, they work less well on low-sulfur coal. The electrical properties of the ash are different.

There is a crash program underway to take the SO_x out of the power plant effluent. Several approaches are under development. Ground limestone can be injected into the furnace, for instance, and calcium nitrates are formed as fine particles which can then be removed by the electrostatic precipitators and the "wet scrubbers" (devices that wash the impurities off the collector walls). There are some of these SO_x control devices on a few existing plants but they have not yet received overall acceptance in the utility industry.

FIGURE 4-3
Deaths and Air Pollution in London, 1952



Deaths, sulfur dioxide concentrations, and particulate mass concentrations during the December 1952 episode in London. (After E.T. Wilkins, *Journal of the Royal Sanitation Institute*, 74, 1, 1954.)

Until such devices are available, the power plants rely on tall smokestacks to disperse the pollutants to the winds. The average height of stacks built in 1969 was 600 feet, and stacks as high as 1,000 feet are being built. (The Washington Monument is 550 feet tall.)

If and when sulfur-removing devices come into practical use, we will see another example of the reach of the energy web throughout one system. In the world about 70 million tons of sulfur are released each year by the burning of fossil fuels. Total world production of sulfur by mining is 30 million tons. Thus, we may see a complete change in the market structure of sulfur and the cessation of sulfur mining as such.

As we look at growth projections in electricity demand (such as are discussed in Chapter 4, Volume II), we see how urgent the solution of the SO_x problem is. The amount of electric energy used may be allowed to quadruple between 1970 and 1990 but we cannot let the SO_x concentrations rise accordingly. Controlling this pollutant will cost both money and energy. The precipitators and SO_x removal devices may consume 3 to 4 percent of the electric energy produced by the plant. They add several tens of millions of dollars to the cost of the plant. The price of these controls or of the damage we have described must be paid for when we buy the convenience of electricity.

The Automobile and Air Pollution

Sulfurous smog is the classical smog which, we read, offended the eyes and noses of 19th-century English royalty. In this country we have, along with our invention of the automobile, invented a new kind of smog. It is this so-called "photochemical smog" that Los Angeles has made famous. It is, unfortunately, now in evidence everywhere that automobiles are clustered.

In photochemical smog the indirect and synergistic effects that we have just described are even more obvious. The troublesome smog components, ozone and the PANs (for peroxyacetyl nitrates), for instance, are not "primary" pollutants emitted by the auto but are "secondary" pollutants formed from the primary ones by action of sunlight (hence *photo*chemical)

The necessary ingredients for this solar stew are the hydrocarbons and the nitrogen oxides from auto exhaust. By a series of complicated reactions, which depend on the energy provided by sunlight, ozone (O_3), a molecule made up of three oxygen atoms, along with a group of complicated organic molecules, and the PANs are produced. These latter are the most irritating components. Ozone is responsible for the sharp, unpleasant odor of smog and with the PANs contributes to eye irritation. It is one of the NO_xs, nitrogen dioxide (NO_2), which gives smog its typical brownish color. Because of the dependence on sunlight, the photochemical smog usually shows up in the afternoon, after sunlight has worked on the lingering exhaust of the morning and previous evening's rush hour.

The hazards of photochemical smog: The irritating effects of photochemical smog are easily demonstrated. It is harder to demonstrate more serious damage to health. Because photochemical smog rarely occurs in intense single periods that can be studied, and does not lead to an easily marked increase in deaths, statistical evidence connecting this smog to deaths is difficult to obtain. It is expected that the more thorough studies under way will tell us more about its effects.

It is the photochemical smog that causes most of the damage to vegetation. Levels of PAN as small as 0.01 or 0.05 parts per million can produce damage within an hour, and ozone is almost as bad. Leafy vegetables are the most sensitive, but even trees can be damaged. It is no wonder that they are replacing real trees with plastic ones along the Los Angeles freeways (and ozone will eventually destroy them).

Carbon monoxide: Another troublesome pollutant from the automobile that co-exists with photochemical smog is carbon monoxide. This odorless, but deadly gas is produced by the incomplete burning of the carbon atoms in hydrocarbon molecules. It is, as we have seen, the major pollutant on the basis of weight: six times as much is produced in auto exhaust as NO_x. It is lethal at levels of 600 parts per million (ppm) and can cause headaches and other problems at 100 ppm. It acts by reducing the mobility of oxygen in the blood, replacing the oxygen molecule in hemoglobin and causing nearby hemoglobin molecules to hold on to their oxygen. It is found wherever automobiles congregate; levels of 50 and even 100 ppm have been found in heavy traffic, automobile tunnels, etc.

Lead: Lead is another poisonous contaminant the automobile favors us with (although there are some industrial sources of lead, and it is released by incinerating certain waste materials). In gasoline, a lead atom is hooked on to a hydrocarbon molecule to slow down the rate of burning and thus prevent premature firing or "knocking." It was the addition of lead that gave automobile engines the sharp efficiency increase in the 1940s that is shown in Figure 3-10, Volume II. It is now an additive to the environment. Studies on the ice sheets in Greenland show its year-by-year increase. It is also found in a city's air in proportion to the gasoline its cars consume. There seems no question of its source.

Its effects, like those of the other pollutants, are difficult to predict. We know it accumulates in bone and in large enough quantity can cause "lead poisoning." We now have, unfortunately, a large exposed population and will soon be able to determine its effects with some precision.

Lead may be the first pollutant to go. It has run into the powerful opposition of the automobile industry because it damages the "catalytic converters" with which they hope to control the other pollutants.

Emission controls: The sources of the various pollutants within the automobile's anatomy are shown in Figure 4-4. Some of these can be handled easily. Evaporation from the carburetor has been reduced by better seals, and the "blowby" gases are being fed back through the engine. The exhaust, however, remains a problem.

It looked easy at first. Since CO and the HCs both result from incomplete burning, their production can be reduced if a "leaner" mixture (increased air to fuel ratio) is used. This, incidentally, is a more efficient mixture (more miles per gallon). The cars in the 1960s were adjusted to leaner mixtures and their CO and HC emissions were reduced. Unfortunately, the leaner mixtures burned at a higher temperature thus increasing the production of the NO_x. The NO_x levels in California did increase in the 1960s while the CO and HC levels dropped. In 1971 the restrictions were extended to include NO_x.

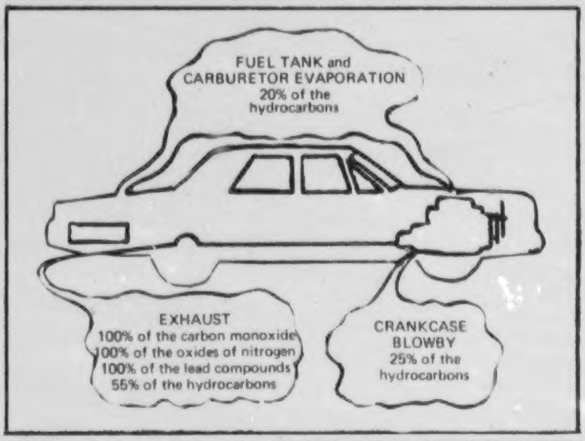
The Clean Air Act of 1970 specified that the 1975 car emit no more than 10 percent of the CO and the HC of 1970 models, and that 1976 models emit no more than 10 percent of the NO_x of 1971 models. Auto companies resisted this edict and implementation was postponed until at least 1977.

Emission reduction in the near future will be accomplished by add-on devices rather than by engine redesign. The current choice is the catalytic converter, which converts CO to carbon dioxide (CO_2) and hydrocarbons to water. They will not at the same time remove NO_x, but the engine can be adjusted to a "richer" mixture to reduce these emissions.

The richer mix and the converters themselves lower gasoline mileage by 7 percent or so, a major argument in the campaign against the restrictions. In fact the mileage penalty is about the same as that imposed by air conditioning and considerably less than that caused by the increasing weight of cars.

FIGURE 4-4

Approximate Distribution of Automobile Pollutants by Source


FUEL TANK and CARBURETOR EVAPORATION
20% of the hydrocarbons
EXHAUST
100% of the carbon monoxide
100% of the oxides of nitrogen
100% of the lead compounds
55% of the hydrocarbons
CRANKCASE BLOWBY
25% of the hydrocarbons

Source: "The Automobile and Air Pollution. A Program for Progress," Part II, U.S. Department of Commerce, December, 1967.

The major problem of the converters is their vulnerability to damage by high velocity lead particles in the gasoline. It is this vulnerability that has caused the demand for unleaded gasoline.

The possibility of reducing exhaust emission by engine redesign has been adequately demonstrated, although American companies have shown little interest so far. The Honda "stratified charge" engine, for example, accomplished pollutant reduction by providing two combustion regions in the engine: a high temperature "rich" region (lowered NO_x) which then ignites a "lean" mixture (lowered CO and HC).

It may be that the combination of fuel shortage and air pollution surplus will eventually bring about, at long last, some radical changes in the American automobile industry.

Air Pollution Meteorology

Before we leave the subject of air pollution, we must balance our emphasis on pollution with a word about air. Since man lit his first fire, he has been polluting the air. Why has it suddenly (so it appears) refused to act as our "disposal"? Most of the answer can be found in the section on growth in Chapter 4, Volume II. The other part of the story we'll tell here.

This "atmospheric disposal" works through two mechanisms, dilution and dispersal. Gaseous pollutants are first mixed in the huge reservoir of air and then dispersed by the winds. Winds, in fact, play a second role as vertical air currents provide for the mixing that accompanies dilution. What has recently become clear is that there are times when the disposal doesn't work.

The great atmospheric engine — its circulating trade winds, cyclones, hot and cold fronts, as well as local currents and breezes are all powered by the sun. All this movement can be traced back to the fact that the ground absorbs more solar heat than the atmosphere, that air near the ground is heated, and that hot air rises.

If a parcel of air near the ground is heated, it expands, becomes less dense than its surroundings and floats upward like a balloon on the cooler, denser air around it. As it rises, however, and keeps expanding, it cools. (Any gas, air included, cools when it expands.) Whether or not it continues to rise depends on whether it becomes as cool as the air around it.

Normally atmospheric temperature decreases with distance from the earth. There are conditions, however, which cause a "temperature inversion," the temperature increases with altitude. Under these conditions the rising, cooling air soon finds itself surrounded by air at the same temperature or warmer. It can rise no more. When there is a temperature inversion, there are no vertical currents to carry pollutant gases away and they hang over us. We have all seen days when smoke flattens out as if against a barrier in the sky.

There are several causes of temperature inversions. Sea-cooled air blowing in over land is part of the Los Angeles problem. A high pressure region caused by subsiding air (air moving toward lower altitudes) is another. The increase in pressure warms the air at lower altitudes. Temperature inversions are a fact of nature. They were not always considered threats; summer "Dog Days," warm, lazy, picnic-times, are generally inversions. It is our overload of the atmospheric disposal that makes us fear them.

A Surplus of Heat

As we stress in Chapter 3, Volume II, all the energy that flows through the many conversion devices of our society eventually ends up as heat. In many cases — in our homes in winter, in a host of industrial processes — heat is the desired product. There are times, however, when heat is a waste product and therefore a pollutant. This so-called "thermal pollution" is one of the growing environmental problems of energy consumption.

There are many industrial processes where heat is used and then must be removed. Water, because it is cheap and plentiful and because it makes good thermal contact and is able to carry a lot of heat energy per pound (more than air, for instance), is the preferred cooling medium. With the rapid growth of energy use, we are in danger of running short of cooling water.

While many processes demand cooling water, 85 percent of the total is used at electric power plants. As we describe (Chapter 3, Volume II), steam turbines, which turn the generators in all but the 15 percent of plants which use water power, are heat engines. To get as high an efficiency as possible the steam leaving them must be cooled. (The technical reasons for this are examined further in Technical Appendix 4 of Volume II.)

The easiest and cheapest (and therefore the traditional) way to cool the condensers of the big steam plants is to pump cold water from a nearby stream or lake through the condenser and discharge the warmed water back into the source. This is called, appropriately enough, once-through cooling. It is the reason most of our generating plants are built near a river, lake, bay, or ocean. To meet our demand for electricity, we've built so many plants that we are in danger of running out of cool water, or at least of raising average temperature in many rivers and lakes, etc. enough to interfere with other uses.

The amount of cooling water we need can be fairly easily computed. The average fossil fuel burning power plant and the present-day nuclear plants are only about 33 percent efficient. This means that two-thirds of the energy released by burning a fuel, or by the nuclear reaction, has to be disposed of. A fossil fuel plant sends about 15 percent of its wasted energy up its smokestack, whereas all the waste heat from a nuclear reactor has to go into the river. To give an idea of quantity needed: a 1,000 Mw coal burning plant needs 12,000 gallons of water per second, a 1,000 Mw nuclear plant needs 15,500 gallons per second when running at full capacity. To give a different perspective, 45 gallons of water must flow through a fossil fuel burning plant for each kilowatt-hour of electrical energy it generates, while a nuclear plant of the same efficiency needs 56 gallons per kilowatt-hour.

The new models of generating plants, nuclear and fossil fuel fired, will be more efficient. (The best plants today are 40 percent efficient.) With improvements taken into account, and using generating capacity growth projections, we compute that by the year 1990 we will need about 350 billion gallons of cooling water per day, a large fraction of the average daily available supply of 1,200 billion gallons. A projection by the Federal Power Commission of the cooling water demand, which takes into account the 30 percent or so that will be satisfied by salt water, is shown in Figure 4-5. Even with some of the load borne by salt water and by cooling towers (which we will discuss later in the chapter), the projected daily fresh water needs amount to one-sixth the average daily fresh water run-off.

This does not mean, fortunately, that one-sixth of our streams and rivers will run through steam plants. Much water will be used over and over. Nonetheless, this is an enormous amount of water and the drain on a river can be heavy during the dry season. The 1,200 billion gallons per day was an average, but two-thirds of the total flows during flood season. The Hudson, for instance, has a flood run-off of 310,000 gallons per second but a low of 15,000 gallons per second during dry periods. This is only enough cooling water for one 1,000 Mw nuclear reactor. It is in the Northeast and the Midwest, where heavy power demands coincide with limited water, that the pinch will be felt.

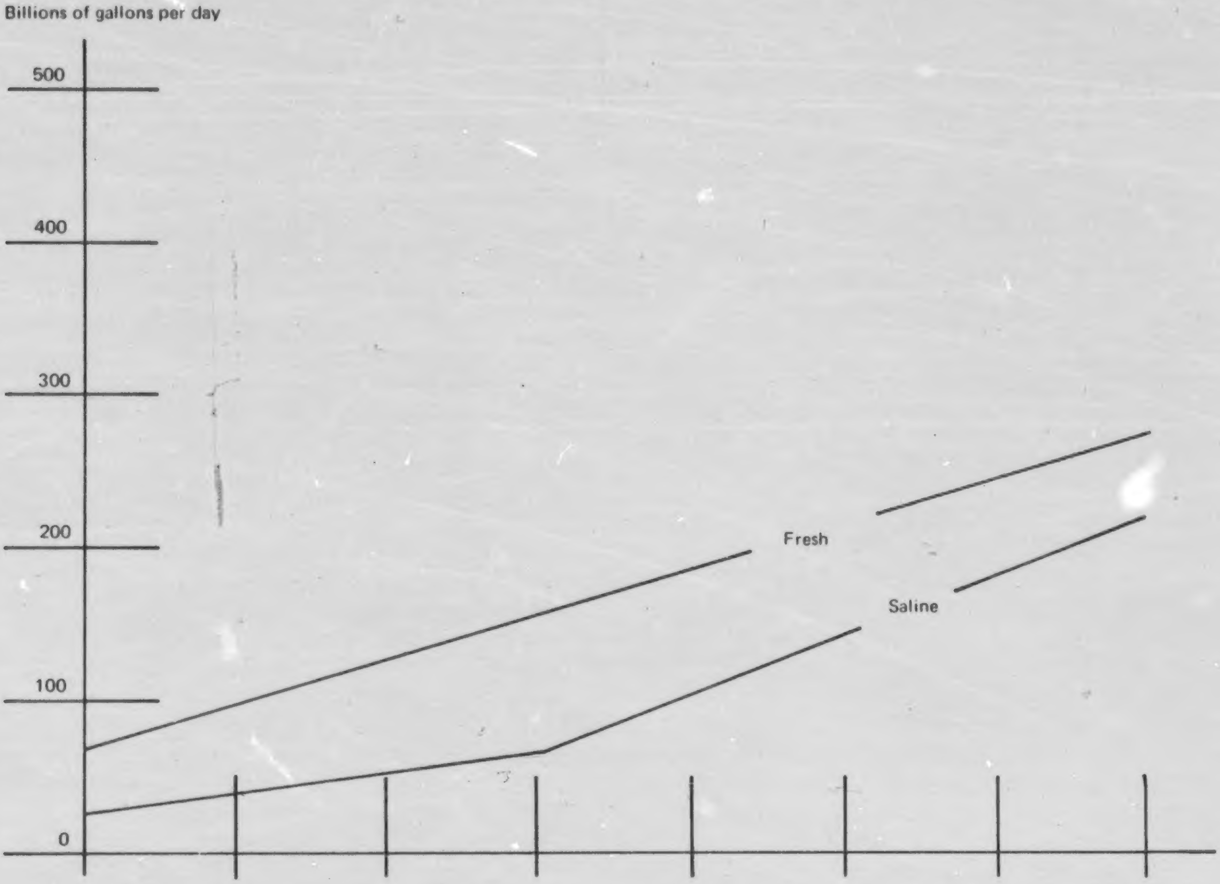
The Effects of Hot Water

Water used in once-through cooling re-enters the river 15 or 20°F hotter than it left. It cools as it moves downstream, but water from a big plant may need 25 miles to cool to the temperature of its surroundings.

Water is a splendid cooling agent. If this were its only purpose, we would have no problem. But water is also used as a drink, a cleansing agent, a recreational medium, a sewer, a transportation medium, and, by aquatic life, as a home. Increasing its temperature affects all these uses in different ways.

The major resulting changes are a decrease in its oxygen holding ability and an increase in the rate at which chemical reactions take place. It is, therefore, cheaper to purify warm water, but, because of lessened

FIGURE 4-5
Water Requirements for Utility Owned Electric Plants



Note: nation's annual average runoff 1,200 billion gallons per day.

oxygen, it cannot as easily assimilate the waste dumped into it.

Temperature is also an important determinant of the aquatic ecosystem. The oxygen demand and the rate of metabolic processes increase with temperature while the oxygen content of the water decreases. Temperature regulates many of the life processes — growth rates, reproduction, respiration and migration, for example.

The reaction to change is varied: what's good for a bass is uncomfortable for a trout, for instance, and at certain critical periods in a fish's life, the livable range of temperature is only 5 or 10 degrees. The most certain statement, therefore, that one can make is that even a small change in temperature will cause a shift in the aquatic ecosystem. With this sensitivity in mind, the recommendations generally are to keep the changes small.

Cooling towers: Although the once-through cooling is the least expensive cooling technique, the technology exists to cool power plants with much less impact on rivers and lakes by the use of cooling towers.

There are two types of cooling towers, wet and dry. In the wet towers, which are now coming into limited use in water-short regions (the Four Corners area, for instance), the warm water is allowed to run down over a lattice work. Air flows past it, either blown by fans or rising naturally ("forced draft" or "natural draft" towers), and the water is cooled by evaporation. These towers still use water, it evaporates, and it has to be replaced; but the total water used is only one-tenth or a twentieth of that used in the once-through cooling.

Wet cooling towers have environmental effects, they change the humidity and can cause clouds and fog. There is also the possibility of damage from the "fallout" of chemicals put into the water to reduce slime growth.

Dry cooling towers are even less environmentally impacting. They are like a huge automobile radiator. The water is not in contact with the air but runs through a system of cooling fins. They are, of course, much the more expensive system.

The cost of cooling: The cost of these alternate cooling techniques has slowed their growth. It is not that they add much to the consumer cost of electricity. (Table 4-1 compares several systems. Additional cost is greatest in the case of the dry towers, but even these towers add only about .05 cents to the present 1.5 to 2.0 cents per kilowatt-hour charge.) The real drawback is the additional investment capital they call for, which ranges (and these are 1969 figures) from $5 million to $9 million for a wet tower to $20 million or $25 million for a dry tower. The problem of investment capital is particularly acute in the money-short mid-seventies.

Thermal enrichment: The ideal solution to the waste heat problem is to stop wasting it. It is a paradox that in a society where half of our energy is used for heating, we waste an additional 20 percent in the form of heat.

There are many schemes for using this heat. In several cities small power plants sell hot water to heat nearby buildings. This is not, however, a realistic option for the sprawling, dirty coal plants or the controversial nuclear plants. Experimental attempts are being made to use the hot water to stimulate growth in marine "food farming," and to heat greenhouses; there are dreams of keeping pavements snow-free and harbors ice-free.

This is an area that needs new ideas, daring planning, and financial support. Each Calorie of "wasted heat" that can be put to use reduces our total energy needs by that Calorie and relieves the environment of the need to get rid of it.

Nuclear Energy: A Mixed Balance Sheet

To discuss the environmental effects, particularly the hazards to humans, of nuclear reactors is to enter a field of raging controversy. It is our intention to stay as far above that controversy as we can. It will not be possible, of course, to stay out of it. We will seem to be pro-nuclear to the "nuclearphobes" and anti-nuclear to the "nuclearphiles."

In the following sections we will describe the kinds of hazards unique to nuclear reactors. They fall into three categories: radioactive pollution, radioactive waste storage, and nuclear accident danger. We will look at specific aspects of these problems and at new, potentially more serious ones that will arise if we begin to rely heavily on breeder reactors. In each discussion, we will indicate the range of uncertainty and the differing viewpoints.

A brief description of the operation of nuclear reactors (both the present Light Water Reactors, LWR, and the Liquid Metal Fast Breeder Reactor, LMFBR) is given in Technical Appendix 6. What follows is a simplified description of these complex devices. We invite the interested reader to turn to that Appendix for more detail.

A nuclear reactor is a device which converts the stored nuclear energy of certain heavy nuclei first to kinetic energy and then to heat energy. The heavy nucleus (uranium 235 in the LWR) fissions, splits into two pieces. These two new nuclei (fission products) are

TABLE 4-1
Comparison of Other Cooling Systems with Once-through Cooling (add-on costs in mills* per kw-hr)

Cooling System	Mills* per kw-hr
Once-through Sea Water	0.03
Cooling Pond	0.03
Wet Mechanical Draft Tower	0.16
Wet Natural Draft Tower	0.14
Dry Towers	0.5**

Source: "Environmental Effects of Producing Electric Power," Part 1. Hearings before the Joint Committee on Atomic Energy, 91st Congress, October and November 1969, Table 1, pg. 1,052.

* A mill is one-tenth of a cent.
** Rough estimate added to original data.

highly radioactive and, therefore, biologically dangerous. The hazards we will discuss derive from the different ways in which these radioactive fission products might enter man's ecosystem.

To focus several pages on nuclear hazards may seem to render a negative judgment on the nuclear reactor as a source of electric power. We do not intend to convey such a conclusion (or any conclusion). We remind the reader that a judgment on nuclear energy must include not only an assessment of these risks but a comparison assessment of environmental damage which would result from the use of available alternate fuels (coal, for example), as well as a recognition of the facts about the demand for electric power (and its growth), the long-range availability of fossil fuels, and the promise of new technology. (These latter three topics are examined in Volume II.) The final judgment on this subject, as on most dealt with in this Source Book, must come from weighing risk and benefit, and that is a personal judgment.

Radioactive Pollution

A nuclear power plant is in several ways environmentally benign when compared to, for instance, a coal-fired plant. It emits no particulates, no SO_x or NO_x. It is a smaller, cleaner, plant site, occupying around 100 acres instead of the 300-400 acres needed for a comparable (1,000 Mw) coal plant, and is free of the daily coal delivery (70 train carloads on average). It causes less land use problems away from the plant. It can be supported annually by 13 acres strip mined for uranium while a coal plant requires 200 acres of strip mined coal land. On the debit side it needs (as we have said) more cooling water, and its pollution is radioactive.

The major source of this radioactivity are the fission products. Some diffuse through the fuel rod coverings, some are released by cracks in the fuel elements, and some radioactivity is formed in the water when its impurities are bombarded by neutrons in the reactor core. All this radioactive contamination is picked up by the water which circulates through the core region.

There are also radioactive gases produced in certain types of reactors (the boiling water reactors, see Technical Appendix 6).

The reactors are carefully designed to prevent large concentrations of these radioactive pollutants from being released to the environment. The water is filtered, held to permit the short-lived radioactivities to die out, and then mixed with the thousands of gallons per second of cooling water returned to the pond, lake, or river. The effluent is carefully monitored with detectors of radioactivity. The gaseous radioactive effluent is also filtered and held for awhile before being released, and is also monitored.

The Effects of Low-level Radiation

In spite of careful design and maintenance, radioactivity is released to the environment where it can enter the ecological food chains or in other ways expose man to its effects. It is established that radiation can do damage. Even in fairly low doses, it can cause cancer, leukemia, or genetic damage. What is not well established is the dose-damage relationship: how much causes what?

There are arguments and counter-arguments. It is not clear, for instance, if there is a threshold dose below which no damage is done or whether any amount of radiation causes some effect. The middle ground is to compare the added exposure we expect from reactors to exposures we receive from other sources of radioactivity in our environment. Such a comparison is made in Table 4-2. It must be remembered that these are averages and that some individuals will receive more exposure and some less than the averages. It is also important to remember that some of these exposures are voluntary and some are not.

If we follow the cautious path of the International Commission on Radiological Protection (ICRP), which sets radiation safety standards, we will assume that no threshold exists; that any radiation exposure, no matter how small, causes some disease and death. We will not be able to say how much or how many; they will be hidden in the greater number of similar illnesses and deaths from other causes. The number may be large, several hundred new cases of leukemia out of the 600,000 expected in the lifetime of 200 million Americans, but the percentage increase in any one individual's chances of getting leukemia is very low.

In the end, the familiar risk-benefit decision is needed: Do we need this power? What are we willing to pay for it?

Radioactive Waste

We have emphasized that most of the radioactive material remains in the reactor; in the fuel elements, in

TABLE 4-2
Average Ionizing Radiation Exposure of U.S. Citizens*

	Milligrams per Year
Medical Exposure – x-rays	
Gonad Dose (Diagnosis, 1964)	55.0
Gonad Dose (Therapeutic, 1964)	7.0
Weapons Fallout Dose (1968)	
(Ca-137: 0.54 mrem, Sr-90: 2.3 mrem)	3.0
Occupational Exposure	
Nuclear Energy Gonad Dose (1970)	0.8
All Other Occupations Gonad Dose (1966)	0.4
Other Man-made Sources	
Gonad Dose (1966)	0.1
Natural Background	
Whole Body	100.0

Source: K. Morgan, **Environment 13**, 30 (January/February 1971).

* The recommended dose limits are 170 millirem per year for genetic (gonadal) exposure and 500 millirem per year for whole body exposure.

fact. After six months or a year, however, these fuel elements must be removed and replaced with fresh ones. After storage for a few months under water to allow the most intense radioactive products to die out, they are shipped, as we described in the previous chapter, to fuel reprocessing plants. Here the radioactive debris is separated from the reusable material.

The radioactive debris is then separated into two waste categories: "high level" and "low level." The high-level waste, our main concern, is "hot" in two senses — it is physically hot because radiation releases energy, and it is intensely radioactive. It must be stored (or disposed of) in a manner that guarantees it will never interact with the biosphere.

Radioactive waste presents us with problems no society has ever faced before. Because some of this radioactive material is long-lived — its half-life* is 30 years or so — we will have the responsibility of safeguarding it for hundreds of years.

Radioactive waste from bomb production has been stored until now in huge underground stainless steel tanks. There are more than 100 million gallons of this high-level waste in tanks at Hanford, Washington, and Savannah River, South Carolina. There have been several instances of leakage which are pointed to by those concerned over reactor wastes.

The present plans for storage call for the liquid to be dried to a brick-like form. Although still radioactive, a considerable reduction in volume is attained. One hundred gallons of the liquid becomes a cubic foot of solid, a year's waste from a 1,000 Mw reactor occupies 6 or 7 cubic feet, greatly reducing needed storage space.

Where to store them is the problem. Salt mines may be the answer. Dry (for millions of years), they also have the desirable property of healing cracks caused by earthquakes. The salt will melt around the hot canisters and seal them.

There is an interesting history of controversy surrounding the AEC's choice of a salt mine in Kansas, near the town of Lyons. The Kansans were not very happy to be selected for this honor and the site itself turned out to be unsuitable and was abandoned. It may be that above-ground storage, at one of the old weapons testing areas, for instance, will be the eventual choice for waste storage.

How much?: The storage problem is only beginning. In Figure 4-6 we show the amount of this waste that will be produced annually between now and the year 2000. By that year, 730,000 cubic feet (a cube is about 90 feet on each side) will need storage. This monument of radioactivity (which, to allow for cooling, will occupy considerably more area than its estimated bulk) must be kept secure for several hundred years. It is a legacy of our use of nuclear reactors which may remain long after we have turned to other sources of electric power.

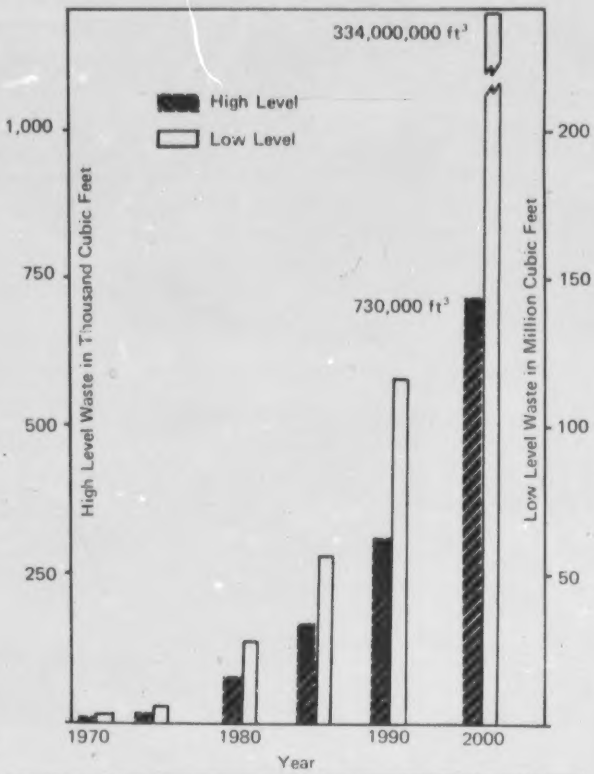
Nuclear Accidents

The real bogeyman of the nuclear power controversy is the possibility of a nuclear accident which would release the radioactive poisons of the core over the surrounding countryside. We will try to examine both sides of this emotion-charged controversy.

It should be made clear from the beginning that nuclear reactors in their present form cannot explode like a nuclear bomb. This can be said only with certainty for the LWRs, for the fissionable element in them, uranium 235, is too diluted in the more common form of uranium (uranium 238) to ever coalesce into a critical mass. It is not clear that other reactors will be this safe. The LWR explosion feared is one caused by the terrific heat energy that would build up if the cooling system were to fail.

Reactors are carefully designed against failure. Safety systems and back-up systems anticipate almost any conceivable failure. Safety is also built into the reactor, the stainless steel pressure vessel around the core will withstand a small explosion, and the entire core is surrounded by a concrete containment structure also able to withstand small explosions. Finally, at least to date, the reactors are required to be built at some safe

FIGURE 4-6
Annual Production of Radioactive Waste



Data from "Draft Environmental Statement, LMFBR Program," AEC, Wash 1535, 1974 distance from any large population center. This last requirement, under the pressure of energy needs, may be the first to be abandoned.

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*The half-life of a radioactive material is the time that it takes for half of a given amount to disappear. Thus, in one half-life half is gone, after two half-lives only one-quarter remains, after three half-lives one-eighth remains, etc.

The record of the nuclear power industry is very good — there have been no deaths from accidents in commercial reactors. But there have been only about 200 reactor years of operation to date. Given the consequences of even one accident, we are understandably interested in estimating the probability and effects of a serious accident.

The accident most feared is a loss of coolant, which would result from a double break in the large pipes that carry the cooling water to and from the reactor core. It is unlikely, but an earthquake, or sabotage, or carelessness could cause it. (This accident is essentially what occurred at the Fermi plant outside of Detroit in the early 1960s.) If this were to happen, the water would be blown out of the reactor by the steam pressure. While the loss of moderator (and the automatic "scramming") would shut off the reactor, the core, because of the high levels of radioactivity in it, would quickly heat up. Within a few minutes, it would begin to melt, unless the back-up emergency core cooling operated at once and successfully. If the core remained hot, a pressure explosion might occur which would rupture the containment vessels, or it could melt through them and perhaps melt its way down into the ground exhibiting what is called the "China Syndrome."

We do not know what will happen. The core cooling is backed up by an emergency core cooling system, and there is great controversy as to whether it will work as well as the theoretical calculations say it will. It has (fortunately) never been tested in actual practice, and it may never be.

In an effort to give a quantitative basis to the estimates of the probability for a serious accident and its consequences, the AEC funded a $3 million safety study at MIT; the results have just been released.[1] The approach of this study was to try to establish a probability for each of the many different failures or malfunctions that could lead to a specific reactor accident, and then by combining these probabilities come up with an estimate of the probability of an accident. They have used a similar approach to estimate possible damages of an accident: What is the probability of a certain direction and speed of wind? How many people are likely to be living in the affected area? How many of them can be evacuated in time? These are the kinds of questions evaluated.

This "WASH-1400" report is over 3,300 pages in length, and we will not attempt a summary here. Tables 4-3 and 4-4 give some of its conclusions and an idea of accident probabilities and their consequences. Table 4-3 presents the "largest accident" conceivable and the average accident. The average accident is 100,000 times more probable; 1 chance in 50,000 per reactor year. If there are 1,000 reactors operating by the year 2000, this translates to 1 chance in 50 for each year of operation that at least one person will receive a serious radiation exposure and $500 million in damage will result.

In "WASH-1400" the risk to an individual from a nuclear accident is compared to other risks; being killed in an airplane accident, for instance, or to being struck by a meteor. (The nuclear risk is closer to the latter.) The dollar damages of nuclear accidents are compared to other man-caused or natural disasters, and it is reported that a nuclear accident causing $1 billion is 100 times less probable than an equivalent man-caused disaster and 1,000 times less probable than an equivalent natural disaster.

"WASH-1400" is already drawing criticism from nuclear skeptics. They point to the great uncertainties of many of the individual probabilities and assert that the final probabilities will have a similar range of uncertainty. In particular, the question of accuracy of the judgment that the emergency core cooling system will work remains the central question. "WASH-1400" gives a rather large probability, 1 in 3,000 per reactor year (which becomes almost 1 for 100 reactors operating for 25 years), for a break to occur in the regular cooling system. If the emergency system doesn't work, then this is likely to become the "Largest Accident" of Table 4-4.

TABLE 4-3
Accident Probabilities Per Reactor Year

1 chance in 150,000 that the accident will involve 10 or more deaths
1 chance in 2,000,000 that the accident will involve 100 or more deaths
1 chance in 100,000,000 that the accident will involve 1,200 or more deaths
1 chance in 1,000,000,000 that the accident will involve 2,300 or more deaths

Source: "Reactor Safety Studies—An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," USAEC, WASH 1400, August 1974.

TABLE 4-4
Reactor Accident Consequences

Consequence	Largest Accident	Average Accident
Death	92	0.05
Acute Illness	200	0.1
Property Damage*	1.7	0.5
Probability (per reactor year)	1 in 5 billion	1 in 50,000

Source: "Reactor Safety Studies—An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," USAEC, WASH 1400, August 1974.

* In billions of 1973 dollars.

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[1] "Reactor Safety Study — An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," WASH-1400, August 1974.

The "WASH-1400" reply is that the judgment of the nuclear engineers is that the emergency system will work 99 out of 100 times. The critic says, "How do you know, since you have no data?" and "What happens if it fails on the Indian Point reactor with a wind blowing toward New York 25 miles away?"

This is about as far as we can go in discussing the safety issue. Those who believe that reactors are as safe as they need be can continue to do so, the unconvinced remain unconvinced. What is lacking is experience — data. The "WASH-1400" study was based on about 100 reactor years of operation, and that experience is not wide enough to provide probability estimates for all the many accident probabilities. It is the best study, perhaps, that could be done with limited data; but it remains, in the end, a projection based on a limited sample. Reactor building continues, there were 52 in operation in September 1974 and 187 under construction or on order. It seems that we shall be accumulating better data year by year.

Plutonium: Before we leave this "what if" land of nuclear energy, we must return again to the controversial new fuel, plutonium. Because plutonium is a fuel and valuable ($10,000 per kilogram) and because it is dangerous, every effort will be made to keep it confined. There remains, however, the possibility that some will escape from damaged fuel elements or during fuel reprocessing. We have already discussed two of the darker sides of this fuel: it will appear at some times and places in the fuel cycle in a form from which nuclear bombs can be constructed, its long half-life (24,000 years) will keep the waste piles hot a long time. There is a third dark facet.

Plutonium is weakly radioactive, it emits a short-range particle (an "alpha particle") which cannot pass through human skin. It does little harm outside the body. If, however, particles of plutonium should get inside the lungs, the story would be different, for there irradiation of the sensitive tissue might produce lung cancer.

The lungs, of course, have defenses which filter out large particles; but plutonium, in its common form as plutonium dioxide, forms particles of a size that can carry into the lungs. There is a danger, therefore, that locally intense radiation may occur from an overall plutonium dose that is very small. This danger from plutonium "hot particles," as they are called, is also a subject of much controversy. There are those who believe that breeder reactors should be ruled out on this basis alone, others point to the existing exposure to plutonium from past bomb testing as evidence that it can't be all that bad.

As in all these cases of controversy over nuclear effects, what is lacking is experimental evidence. Plutonium is an artificially created nucleus. It has only been around for 25 years, and reasonable medical statistics on it only go back to about 1964. Since cancers take 15 to 30 years to develop, we must wait for our answers a few more years. A resolution of this problem may be the most important determinant of the future of nuclear energy.

Long-range and Large-scale Effects

We have so far dealt with localized effects: air pollution over cities, local heating in a river, and the intense radioactivity of stored reactor waste. We must now give consideration to some seemingly small effects which have global significance and may, in the long run, have more important consequences than all others. The most important of these is the increase in carbon dioxide (CO_2) in the atmosphere. This molecule is formed whenever carbon is burned. As we burn the fossil fuels, therefore, we release it to the atmosphere. Such measurements as we have, show that the amount of CO_2 in the atmosphere has increased over the past century by about 10 percent.

In the atmosphere CO_2 plays a sensitive role. It acts as a "window" to radiation allowing the incoming sunlight to pass through, but absorbing heat radiated out from the earth and reradiating some of it back to the earth. This is called the "Greenhouse Effect" because the glass in a greenhouse acts in a similar fashion. The effect of an increase in CO_2 will be to warm the atmosphere.

Fortunately all the CO_2 from fossil fuel burning does not stay in the atmosphere; one-half to two-thirds of it is absorbed by plant life or in the top layer of the ocean. With that reduction taken into account, it is estimated that the CO_2 added to the atmosphere will be twice the 1970 levels by 1990, and that by the year 2000 the increase over the 19th-century levels will be 25-30 percent. Burning all our fossil fuel resources might increase the amount by as much as fourfold.

Since the CO_2 levels have measurably increased, we can look for changes in atmospheric temperature in this century. What we find is an increase of about 0.6°C from the end of the 19th-century until about 1940 and since then a 0.2°C cooling. These are small changes, but climate is so sensitive to temperature that the 0.2°C cooling has been accompanied by increased sea ice in the North Atlantic, the growth of glaciers, and changes in the rainfall patterns.

Nature has made the point that small changes are often associated with large effects, but we are left to wonder why the temperature dropped instead of increasing. There is speculation that a different pollutant, dust, is causing this by reflecting some solar radiation back out into space. The jury is still out and it may be that the two effects are cancelling. What is clear, however, is that the buildup of both types of pollutants will bear careful watching.

Direct heating: With this worry over small changes one might begin to worry about the one inescapable pollutant of energy conversion — heat. It is the end product of all the energy we use. On a global basis we are fairly safe, our total energy release is only about one one-thousandth of the average incoming heat from the sun. In local areas we make a more impressive showing. In the 4,000 square miles of the Los Angeles basin, for instance, man's heat generation is about 5 percent of the incoming solar energy. By 2000 it may be almost 20 percent.

What we threaten by heat release is the radiation balance of the earth — the difference between the incoming and outgoing energy. This is again a very sensitive balance, a change by a few tenths of a percent would, it is claimed, melt all the polar ice. The effects are miniscule at present, only a thousandth of a percent, but we cannot afford many more energy doublings.

Cities as heat islands: We have already changed the climate locally. Our cities now are "heat islands,"* 10° to 20° warmer than the countryside, causing changes in rain and snowfall, in wind speeds, fog coverage, etc. All the changes, however, are not energy-related. A city's tall buildings act as a heat trap for incoming radiation, the asphalt and concrete stores it, and there is little grass to dissipate it by evaporation. Most of this extra heat, therefore, comes from the sun and only one-fourth or so from the consumption of energy (although the percentage may be higher in the winter).

We are beginning to make a difference in global patterns. Since we are fooling with massive mechanisms, this difference will require careful study, and a continued increase in energy consumption will need a long preview.

Fusion and the Environment

We will close this long list of energy-environment relationships by looking beyond this century to the energy source we hope will be important in the next one. What is the expected environmental impact of fusion?

This other "Big If" of the future (along with the solar generation of electricity) is discussed in Chapter 7, Volume II. While fusion reactors will not be as environmentally benign as solar energy devices, they have (as far as we can judge at present) less potential hazard than the fission reactors. The process itself produces only one radioactive residue directly, the radioactive form of hydrogen called tritium. Tritium can be of some danger as it will combine with oxygen to form water, and water, of course, is biologically important. Tritium, however, is a fuel for fusion rather than a waste product and so the incentive to control and retain it is very high. It will be economically, as well as environmentally, unwise to let it pollute.

Other radioactive products will be formed by neutron bombardment of the material of the fusion plant, but the amount of this will be one-tenth or a hundredth of that produced per kilowatt-hour by fission plants.

Fusion also will reduce worries about "nuclear accidents." The threat of an explosion is much less, there is no chance of a "critical mass" effect, and little radioactive debris to be spread around. Of equal importance is the fact that bomb materials are not made in the fusion process, we will not have to worry about hijacking, nuclear blackmail, etc.

At this long range, therefore, fusion looks to be a source of relatively clean energy. We will have to watch the total heat release but can perhaps relax our vigilance elsewhere. This view is at long range, however, and the true environmental impact will emerge step by step as we move into future.

Summary

This chapter finishes the triumvirate on environmental effects of energy. We looked at these effects at the source, during delivery, and at the point of use.

The major environmental effects of energy consumption fall into three broad categories: air pollution, heat pollution, and nuclear energy hazards. From a different point of view, we could have used two other headings — the environmental effects of electricity generation and of automobile use. The generation of electricity claims a share of all three pollution categories, while the automobile owns much of the air pollution category.

In the discussion of air pollution we assigned the presence of 75 percent of the carbon monoxide, 53 percent of the hydrocarbons, and 47 percent of the nitrogen oxides to the automobile; and 73 percent of the sulfur oxides plus 42 percent of the nitrogen oxides to the fossil fuel burning power plants. Of the fossil fuels, coal is the chief offender.

Electric power generation is responsible for most of the cooling water demand, 85 percent of the total. It may use as much as one-sixth our total average fresh water run-off by 1990. The switch to the nuclear reactor will not help here, as it demands more water than the fossil fuel plants.

The nuclear power plants are new on the scene, but they have not come quietly. There has been much protest and concern. Environmentally, criticism has had three foci: radioactive pollution, radioactive waste, and the danger of nuclear accident. Recently a concern over the threat of plutonium in the lungs has been added. As is often the case, these controversies continue strong because scientific data are lacking. Nuclear energy is too briefly with us. In most of the specific instances, however, concern is over statistically improbable but individually large effects. The pro and anti-nuclear positions usually involve more than the effects themselves. They are based on a complete and often hidden personal risk judgment. This is as it should be. It is to facilitate these, and related judgments, that the facts of this Source Book have been assembled.

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*Heat Islands — the city atmosphere is warmer than the surrounding atmosphere.

CHAPTER 5

Energy and the Economic System

Energy and the Economic System

The production, delivery and consumption of energy all have impact on the natural environment, and either directly or indirectly, on man's physical and psychological well-being. We have examined the most important impacts in the previous three chapters and have pointed to ways in which harmful ones could be lessened. What we saw emerging were heretofore hidden costs of energy. It is becoming clear, however, that such costs cannot continue to be hidden, that dollar signs must be put on them so that they can give appropriate signals in the marketplace.

In this chapter we will not be so subtle. We will deal with energy as a commodity whose buying and selling is already part of the marketplace. We will follow the threads of the energy web into that complex region of society where men buy and sell, produce and consume.

Energy has many different contact points in the economic system and there are many relationships to investigate. We will look, for instance, at the relationship between energy and economic growth, energy and employment, and energy and affluence. We will take a look at the role of energy in food production, since the food crisis is also one of major concern.

We will also look specifically at some other dollar signs, at the need for dollars to increase the rate of energy extraction and to increase our capacity of electric power generation. We will finally estimate the size of the dollar investments needed to repair and protect the environment.

We begin with a national perspective and examine the role of energy in stimulating the ever-growing production of goods and services by which the wealth of America is measured.

Energy and Economic Growth

In Chapter 4, Volume II, we look at some of the upward-swinging curves that are a mark of the "Exponential Century" in which we live. We show growth in total national energy consumption and in individual (per capita) consumption. That overall growth is reflected in similar growth curves for the production and consumption of many forms of energy (especially the popular forms: oil, natural gas, and electricity).

Over the same time-scale, America's population has been growing as has her affluence — if the latter is measured by personal income and gross national product.* Since the sufficiency of our energy supplies is now in question (at least their sufficiency at a price we can afford), we need to try and discover just how energy-dependent our economic growth is.

Energy and the GNP

The traditional measure of a country's economic well-being is the GNP. A large per capita GNP indicates national wealth, and the potential, at least, for the civilized lifestyle we associate with national wealth. Among the goods included in the GNP is energy — the value of the fossil fuels, and the uranium and electricity that are consumed. Energy also contributes directly to the GNP those dollars used to extract, ship, and refine fuels and to generate electricity. The direct energy contribution to the GNP, even taking into account all the dollars generated by the activities we have just mentioned, is not large, no more than 10 percent of the total.

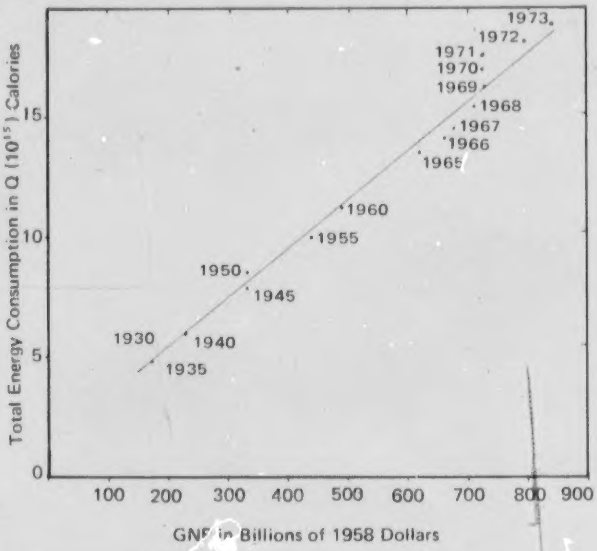
Energy has a much larger indirect effect on the GNP, of course. In some industries, the plastics or aluminum industry, for example, it is essentially a raw material, and in all industries it is energy plus labor that produces goods.

It would be surprising, therefore, not to find some relationship between the total consumption of energy and the GNP.

In Figure 5-1 we have plotted the United States GNP (in 1958 dollars) against the total United States consumption of energy for the past 40 or so years. It is hard to avoid the judgment that there is a fairly strong connection between the two. As energy consumption increases, the GNP goes up (or vice versa; it is difficult to say which is leading and which is following). We get some independent evidence on this last question from the results of the oil embargo (see Chapter 1, Volume I). When energy consumption was forced to decrease, the GNP also declined.

It should be said quite firmly at this point that although the evidence drawn from Figure 5-1 and from the oil embargo experience suggests a relationship between energy and the GNP, it does not *prove* that one exists and certainly does not prove a one-to-one correspondence. In particular, we cannot draw the conclusion from these data that a policy of conserving energy will

FIGURE 5-1
U.S. Total Energy Consumption Versus GNP, 1930-1973



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*The gross national product, GNP, is the dollar value of the goods and services produced by a country.

necessarily cause a reduction in the GNP. What happens depends very much on how we reduce energy consumption. We will gain further evidence on this when we examine the ratio of energy consumption to the GNP in a later section.

We can strengthen our premise that there is a strong relationship between energy consumption and GNP by looking at these two quantities for many different countries. Since countries vary so much in population, and since more people should be able to produce more goods, what we will compare is the per capita (per person) GNP to the per capita energy consumption. We show these data for a selection of countries in Figure 5-2.

There is certainly a rough correspondence between energy and GNP in these countries. Most of the points fall on or near the line we have drawn in Figure 5-2. From this we can say that it takes about 16,000 Calories of energy to produce a dollar GNP. The United States sits somewhat to the left of the line, which means that it produces less dollars per Calorie than the average country.

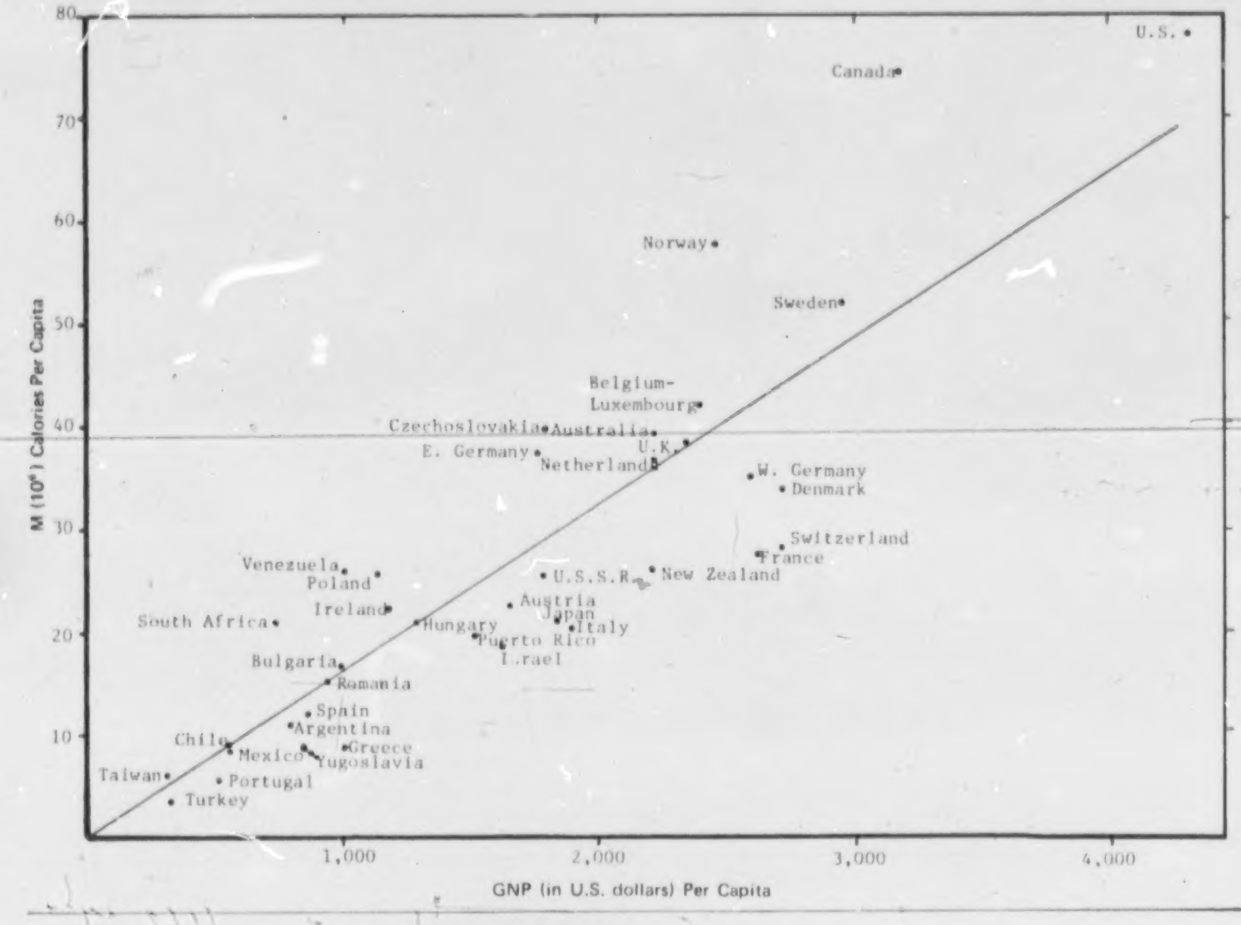
There are many more interpretations which could be read into this comparison. We could look at it country by country and try to find out why, for instance, South Africa, Canada, or Norway uses so much more energy to produce a dollar GNP than does Japan or France. The answer would no doubt be found in the different industrial structures. Canada, South Africa, and Norway have energy-intensive primary metals industries while Japan and France get much of their GNP from manufacturing finished products out of these metals (and other materials) and their input is skill and knowledge rather than energy. The former countries are also blessed with inexpensive hydroelectric power. We can attribute the greater-than-average ratio of energy to GNP dollars in the United States to the fact that energy has been relatively inexpensive in this country.

Summarizing Figure 5-2, we can conclude that there is a relationship between energy consumption and affluence (at least to the extent that the latter is measured by GNP). To have a large per capita GNP one needs to use lots of energy. The great variations in the energy to dollar ratio, however, show us that energy by itself is not enough, that future growth of the GNP is not absolutely tied to future growth in energy consumption.

Another interesting aspect of the relationship between energy consumption and GNP emerges if we plot

FIGURE 5-2

Per Capita Energy Consumption Versus GNP, Selected Countries, 1968



the ratio of total energy consumed to the GNP. This number tells us roughly how many Calories are needed to produce one dollar in the GNP. The historical record of this ratio in the United States since 1947 is shown in Figure 5-3. What we see in this figure does not show up in the earlier one. It tells us that although there is a relationship between the consumption of energy and the GNP, the ratio fluctuates. Even more important, it shows that over the 20 years from 1947 to 1966 the ratio, although fluctuating, dropped steadily. We interpret this as meaning that over the period it took less energy each year to produce a dollar of GNP. Alternatively, we could say that the efficiency of energy utilization (as measured by the production of GNP dollars) was increased. This period of increasing dollar production efficiency corresponds to a period in which energy conversion efficiency was also increasing (some examples of this are shown in Chapter 3, Volume II).

In the four years 1967-1970, the ratio stopped decreasing and the amount of energy needed to produce a GNP dollar increased each year. This caused considerable consternation as it suggested that the efficiency of energy in producing money had stopped improving. Since the ratio went back to its downward trend in 1972 and 1973 we are uncertain about the long range trend. The upswing of the ratio in the late 1960s does warn us, however, that it is dangerous to assume this ratio will continue to drop.

The speculation about the continuance of this relationship is important only because of the view of the future it might give us. One of the energy policy options we will consider is the emphasis on energy conservation. (We discuss this in detail in Chapter 6, Volume I). If a reduction in energy consumption means a reduction in GNP, this option will not be very enthusiastically accepted. Since most of the drive toward conservation will be aimed at using energy more efficiently, however, we can hope, at least, that this form of energy conservation will cause an *increase* in the efficiency of producing GNP dollars (to correspond with the 1947-1966 period) and that the GNP will continue to grow faster than energy consumption.

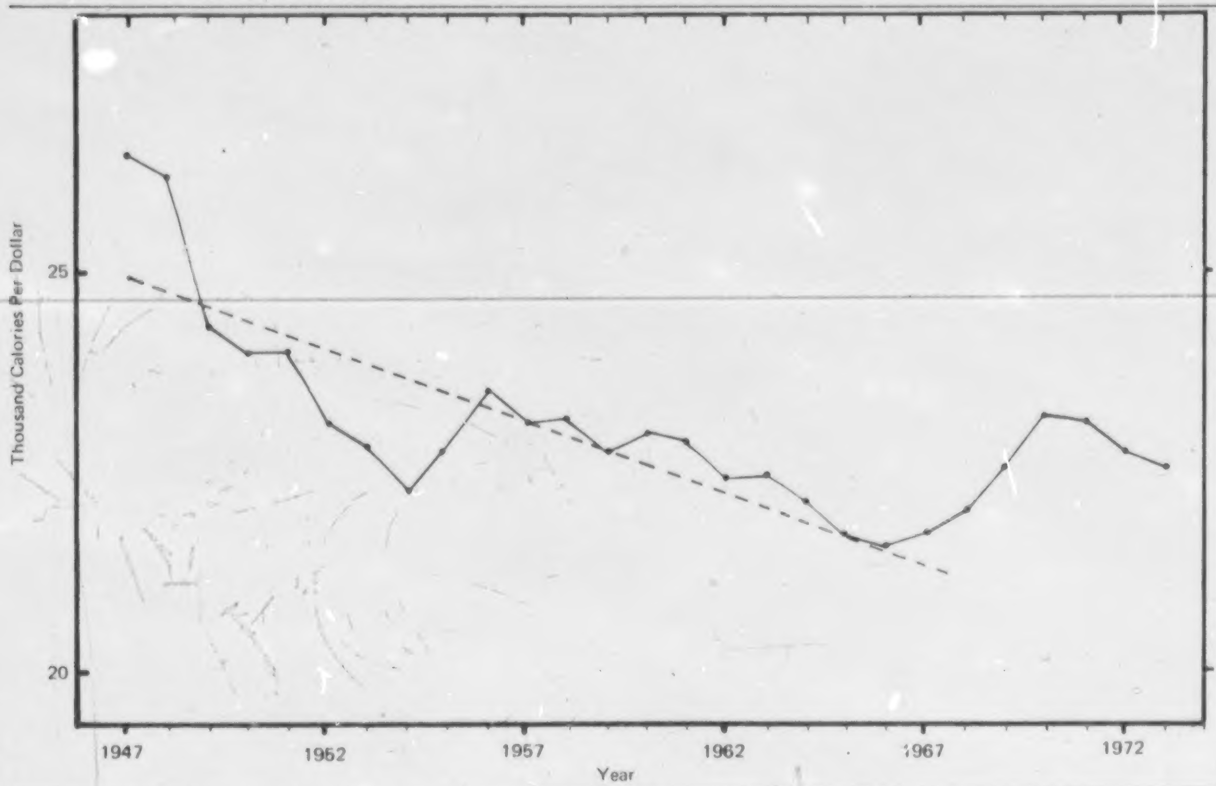
Energy and People

More important than the relationship between energy and the nation's financial status is the one between energy and individual finances. We will investigate both ends of this relationship between energy and people: energy and employment and energy consumption as a function of personal income.

Energy and Employment

Evidence of the strong tie between energy and employment is not difficult to find. The oil embargo showed a direct connection. The sudden reduction in oil consumption forced on us resulted in the temporary loss of some 500,000 jobs. Most of these were in industries that deal

FIGURE 5-3
Energy to GNP Ratio, U.S., 1947-1973



with energy directly — service stations and airlines, for instance — with the others in the automotive and automotive-related industries.

There are also many examples of longer-range changes in which energy played an essential role. When the gas pipelines were finished in the post-war years and natural gas became available in the East, it displaced coal from many markets. The consequent loss of 300,000 jobs in the coal industry since 1947 created problems for Appalachia which have never been really solved.

Changes in the total energy consumed and in the mix of energy forms in use have their greatest impact on two industry groups: those that produce energy as a product and those that use large amounts of energy essentially as a raw material. We will look at employment levels and trends in these groups in order to obtain some guidelines to possible effects of changes in energy consumption.

Employment in the energy industries: The energy industries are those which extract, refine, distribute, and sell energy. The major industrial groups are: coal mining; oil and natural gas extraction; coal and petroleum refining; pipeline companies; utilities (both gas and electric); the wholesalers of gas, oil and coal, and the retailers—gasoline service stations and heating oil dealers.

In Table 5-1 we provide a breakdown of the role of the energy industries within the economy. The energy industries as a group account for only 3 percent of total employment and contribute 12 percent of the "value added."* They are, for the most part, "capital-intensive" industries, that is, they rely on capital (for machinery, plants, etc.) rather than labor for their productivity.

Employment in all the energy industries has increased only 5.5 percent from 1950 to 1971. (Total United States employment increased 41 percent during that period.) Most of the increase came in the utilities and fuel marketing industries. Employment, in fact, decreased in mining, refining, and the pipeline industry. A summary of employment changes is given in Table 5-2.

Employment decrease was brought about by the replacement of men by machines and thus, to a considerable degree, of men by energy. It is only in the service categories (service station attendants, utility repairmen, etc.) that employment has grown.

The continued growth in energy demand, and specifically the growth in the utility industry, will create new demand for manpower. Much of this manpower will have to be technical and skilled. The building of refineries, the opening of new mines, and the building of utility plants will also make demands on the construction industry. Tables 5-3 and 5-4 are projections of manpower needs in critical occupations from the FEA Project Independence report. We see the urgent need for nuclear engineers, health technicians, and millwrights, for instance, and the necessity to double the number of engineering and science technicians each year from 1978 to 1980. We need to begin the flow of these future employees through our schools immediately if we are to meet the manpower demand of the late 1970s.

Employment in energy-intensive industries: The other group of industries directly affected by changes in the availability and price of energy is that in which large amounts of energy is used in production. (We list the six most energy-intensive industrial groups in Table 3-11, Volume II, and indicate the amount and form of energy each uses.) The most energy-intensive industrial groups are the primary metals, chemical, food, and paper industries, and the manufacturers of stone, bricks, cement, etc. (Petroleum refining is contained in this group in Table 3-11, Volume II, but, for this discussion, we include it with the energy industries.)

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*The value added is the difference between the value of the product delivered and the cost of the raw materials, labor, and energy to produce it.

TABLE 5-1
The Role of Energy Industries in the Economy (by percent), 1971

Economic Measure	All Energy Industries	Coal & Oil Production	Coal & Oil Refining	Pipelines	Utilities	Wholesale	Retail
Employment	3.0	0.54	0.26	0.02	0.89	0.29	0.97
Production Value Added*	12.0	5.12	1.80	NA**	5.07	NA	NA
Plant and Equipment Investment	27.0	2.2	7.2	0.1	17.3	0.4	0.3
Construction Investment	15.2	NA	NA	0.33	14.50	NA	NA

* The "value added" is the difference between the value of the product delivered and the cost of the labor and energy to produce them.
** NA means not available.

Data from: "A Time to Choose," final report of Energy Policy Project, Ford Foundation, Cambridge, Massachusetts: Ballinger, 1974.

The record of employment from 1950 to 1971 for this group is included in Table 5-2. The energy-intensive industries, as a whole, employ only 7 percent of the nation's workers and consume some two-thirds of industry's share of energy. Overall employment in these industries has increased only 2.5 percent. Their consumption of energy, however, increased 106 percent over the same period.

These are also "capital-intensive" rather than "labor-intensive" industries. Machinery and electricity have been increasingly substituted for manpower.

Energy and employment; a summary: The energy industries and those for which energy serves as a raw material account for only 10 percent of the total work force. Although certain industries (utilities, gas and oil retailers, chemical and paper) have shown significant increases in employment since 1950 (but none as high as the average increase of 41 percent) the group as a whole has remained largely static. Thus the few-percent change in the total amount of energy consumed under the various energy policy options open to us will not be expected to cause large changes in employment.

TABLE 5-2

Total Employees in U.S. Energy Industries and U.S. Energy Intensive Manufacturing Industries, 1950-1971

Industry Classification	1950	1971	1950-1971 (Percent Change)	Percent of 1971 Total Employment
Total Employment in U.S. Energy Industries	2,075,000	2,190,000	+5.5	2.96
Anthracite, Bituminous Coal & Lignite Mining	441,000	138,000	−69.0	.19
Oil & Natural Gas Extraction	266,000	261,000	−2.0	.35
Petroleum & Coal Products	218,000	191,000	−12.0	.26
Pipline Transportation	24,000	18,000	−25.0	.02
Electric Companies & Systems	239,000	296,000	+24.0	.40
Gas Companies & Systems	118,000	168,000	+42.0	.23
Combination Companies & Systems	169,000	190,000	+12.0	.26
Petroleum Bulk Stations, Terminals & Other Wholesale	131,000	212,000	+61.0	.29
Gasoline Service Stations	469,000	618,000	+53.0	.84
Fuel & Ice Dealers	NA	99,000	NA	.13
Total Employment in Energy Intensive Manufacturing	4,709,000	4,828,000	+2.5	7.31
Primary Metals	1,247,000	1,178,000	−5.5	1.6
Stone, Clay, and Glass	547,000	588,000	+7.5	.8
Food & Kindred Products	1,790,000	1,582,000	−11.6	2.1
Paper & Allied Products	485,000	635,000	+30.9	.9
Chemicals & Allied Products	640,000	845,000	+32.0	1.1
Total Employment in U.S. Energy Industries & Energy Intensive Industries	**6,784,000**	**7,603,000**	**+12.1**	**10.27**

Source: "A Time to Choose," final report of Energy Policy Project, Ford Foundation, Cambridge, Massachusetts: Ballinger, 1974.

TABLE 5-3

Critical Occupations, Energy Operation and Maintenance, and Projected Growth of Energy Sector Employment Compared to Total Economy, 1970-1985

	Energy Sector Direct Production Employment 1970	Energy Sector Requirement in 1985	Percent Growth in Energy Sector 1970-85	Average Annual Growth in Energy Sector 1970-85	Average Annual Growth in Total Economy 1970-80
Nuclear Engineers	1,038	5,295	409.7	27.3	NA
Metallurgical Engineers	418	1,051	151.4	10.1	2.9
Mechanical Engineers	6,976	13,149	88.5	5.9	2.2
Health Technicians	313	1,345	329.6	22.0	NA
Physicists	808	1,896	134.6	9.0	2.6
Electricians	18,081	25,768	43.6	2.9	2.3
Plumber/Pipefitters	7,477	12,581	68.3	4.6	3.0
Mine Operators NEC*	113,316	129,642	14.4	1.0	−1.9
Millwrights	426	1,221	187.0	12.5	1.2
Power Station Operators	20,495	35,671	74.0	4.9	−0.6

Source: "Project Independence Report," Federal Energy Administration, 1974, Table V-32.

- NEC means not elsewhere classified

That employment may not be overly sensitive to total energy consumption was borne out by studies undertaken by the Energy Policy Project of the Ford Foundation. The project report compares the employment results of three different policy options.* As shown in Figure 5-4, total energy consumed in 2000 will differ by almost a factor of 2 between the extreme options while total employment is expected to remain about the same.

It is, in fact, possible to conceive of an increase in employment in a future with reduced energy consumption. A swing away from the capital-intensive energy industries to labor-intensive service industries would increase employment. As just one example of a low-energy future with higher employment, we can point to the energy savings that would accrue from building fewer automobiles, but building them to last. We would find, in all likelihood, that more man-hours per car would be required to build to more stringent standards, but that whatever employment loss occurred would be compensated for by an increased need for repair and servicemen. The example also shows, however, that changes in the energy-employment picture must have long lead times in order to provide the training and retraining the job changes will require.

Energy and Personal Income

It does not appear from the previous discussion that a drastic decline in employment is a necessary consequence of a reduction in energy consumption nor, in fact, that an increase will increase employment. Energy and many of the goods for which it is an important raw material make a bigger impact on capital gains and losses than on employment. We are, therefore, led to

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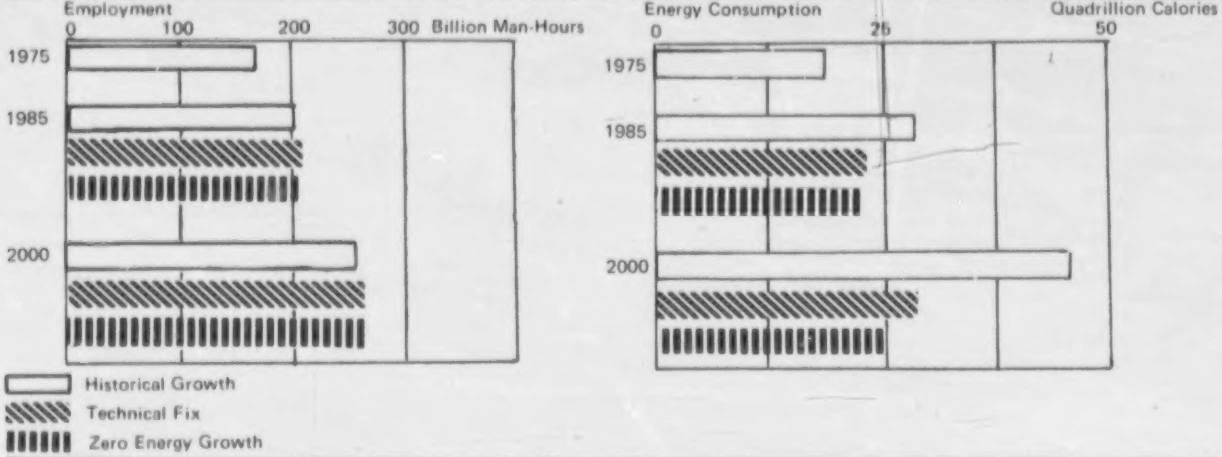
*These options will be discussed further in Chapter 6, Volume I.

FIGURE 5-4

Employment and Energy Consumption Under Different Options



Source: "A Time to Choose," final report of Energy Policy Project, Ford Foundation, Ballinger, Cambridge, Massachusetts, 1974, pg. 91.

TABLE 5-4

Critical Occupations, Energy Related Construction

	Projected Energy-Related Construction Equipment 1975[1]	Energy Construction Requirement 1978-1980[2]	Average Annual Growth in Energy Construction 1975-1980	Average Annual Projected Growth in Total Construction Employment 1973-1980
Pipefitters/Plumbers	15,398	31,998	21.6	1.9
Welders	5,782	10,480	16.3	3.7
Electricians	8,639	17,393	20.3	1.3
Boilermakers	1,764	3,810	23.2	–2.9
Millwrights	3,870	8,316	23.0	–4.7
Carpenters	2,760	5,454	19.5	–0.9
Electrical Engineers	1,038	1,961	17.8	4.7
Geologists	264	486	16.8	6.6
Engineering & Science Technicians NEC*	596	2,035	48.3	42.1
Draftsmen	3,237	4,852	10.0	10.0

Source: "Project Independence Report," Federal Energy Administration, 1974, Table V-33.

[1] Survey by National Planning Association

[2] Average annual employment

*Not elsewhere classified

wonder what happens at the other end of the energy flow. Who buys it, in what form, and how much?

In several chapters of this Source Book (notably Chapter 3, Volume II) we look at average consumption patterns. We see that within these averages on a worldwide basis there are large disparities — that an average American uses about 50 times the energy an average Indian does. Are there similar disparities in our own country?

According to a recent survey[1] the average American household consumes a total of 86 million (M) Calories of primary energy each year. Six percent of the income of this average household is spent for this amount of energy, the equivalent of 848 gallons of gasoline, 142,000 cubic feet of natural gas (for heating and cooking) and 8,000 kilowatt-hours of electricity (the primary energy used to create this electricity is also included in this summary).

The first departure from this average comes if we look at household energy use as a function of income level. We see in Figure 5-5 that although there are small differences in the use of basic energies — electricity and natural gas — over the range of incomes studied, the biggest difference is in gasoline consumption. The ratio of total consumption in the "well-to-do" household to the total consumption in the "poor" household (as defined in Figure 5-5) is about two to one, a much smaller ratio than that of their respective incomes. There is only so much direct energy one can use.

This last observation suggests that the poor may spend a larger share of their income on energy than do the rich. The data of Figures 5-5 and 5-6, summarized in Table 5-5, bear this out. The poor use less energy than the rich but spend a larger share of their income for it. And they pay more per Calorie for it, also, at least in the case of natural gas and electricity, for which rates are lower for the large-volume user.

The study goes on to look at the various end uses for energy and at the rich/poor differential. It found, for instance, that although the poor live in smaller houses and apartments, they are less well-insulated, and as a result they require about as much natural gas to heat as do the houses of those in higher-income brackets.

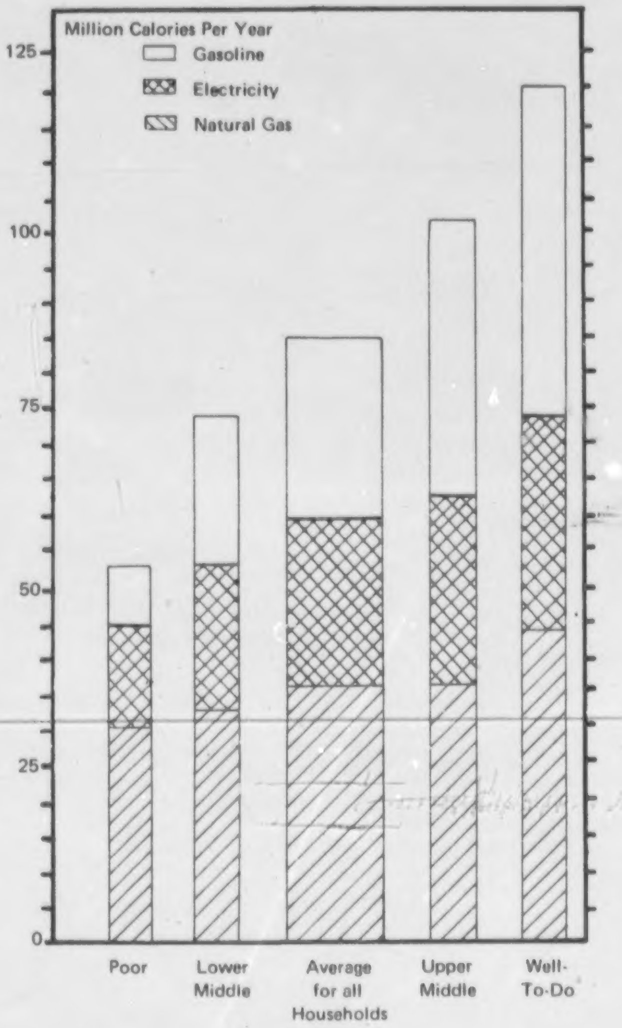
The data on appliance ownership by income group is also pertinent to the energy future. These are collected in Table 5-6. It is interesting to note that the definition of "poor" is a relative one, since a quarter of the households in that group own color televisions, frost-free refrigerators, etc.

One of the energy traps the poor are caught in (and they are joined there by many from other income groups) is that they do not have enough cash to save energy. They cannot insulate or buy storm windows. They are stuck with first-cost comparisons, they have to buy the cheapest refrigerator, air conditioner, etc., and as we find in study after study, the least expensive energy-converting device is often the least efficient one. We return to this subject in Chapter 6 where we look in more detail at some energy-conserving strategies.

The greatest energy-use gap between rich and poor is in the transportation sector. (This is shown by the large difference in gasoline consumption we saw in Figure 5-5.) Seventy-nine percent of well-to-do households own two or more cars, while nearly half the poor own none. Thus those households in the low-income 17 percent use only 5 percent of the total gasoline consumed.

We have, so far, looked at the disparity in direct energy use of fuels or electricity. There is also an obvious difference in the sharing, among income groups, of

FIGURE 5-5
Household Energy Use by Income Group



Source: Washington Center for Metropolitan Studies.

Note: Includes only natural gas, electricity, and gasoline.

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[1] A national survey by the Washington Center for Metropolitan Studies reported in "A Time to Choose," the final report of the Energy Policy Project of the Ford Foundation (Cambridge, Massachusetts: Ballinger Publishing Company, 1974).

TABLE 5-5
The Percentage of Family Income Spent on Energy Declines as Income Increases

Income Status	Average Income	Average Annual Calories (Millions per Household)	Average Annual Cost per Household	Percent of Total Annual Income Spent on Energy
Poor: Total	$2,500[a]	52	$379	15.2
Natural Gas		30	147	5.9
Electricity		14	131	5.2
Gasoline		9	101	4.0
Lower Middle: Total	$8,000	74	572	7.2
Natural Gas		33	153	1.9
Electricity		20	167	2.1
Gasoline		22	252	3.2
Upper Middle: Total	$14,000[b]	102	832	5.9
Natural Gas		36	166	1.2
Electricity		27	213	1.5
Gasoline		39	453	3.2
Well Off: Total	$24,500[b]	121	994	4.1
Natural Gas		44	200	.8
Electricity		31	261	1.1
Gasoline		46	533	2.2

Source: Washington Center for Metropolitan Studies Lifestyle and Energy Surveys, 1972-1973.

Note: Electricity and natural gas expenditures based on billing data received from utilities. Gasoline expenditures estimated from respondents' quantitative information and the average 1972-1973 price of 37¢ per gallon.

[a] 77 percent of the poor had incomes less than $3,000.

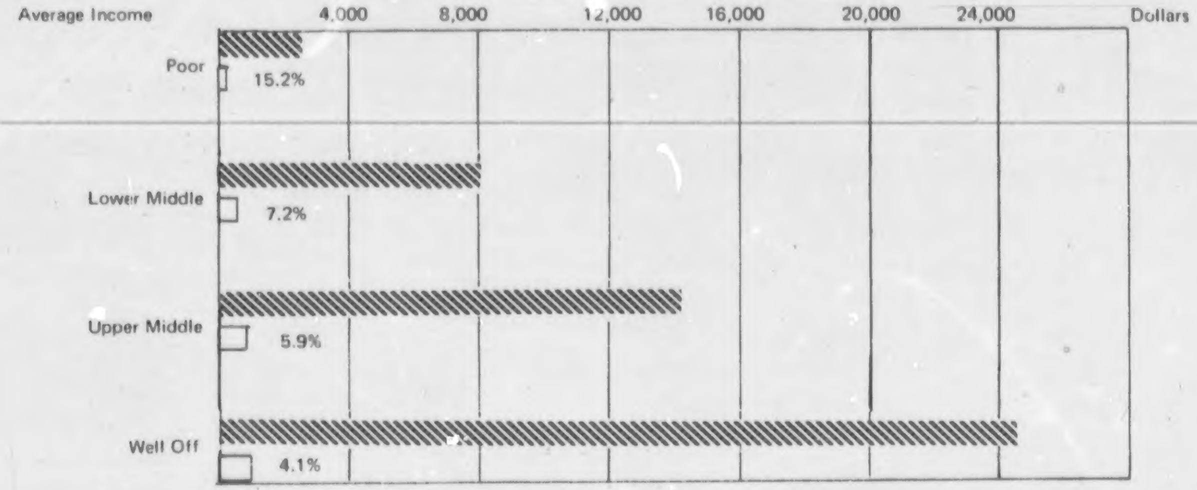
[b] Calculated from unpublished census data.

TABLE 5-6
Percentage of Households Owning Major Appliances, by Income Group

Appliance	Poor	Lower Middle	Upper Middle	Well Off
Stove	95	97	99	98
Refrigerator				
Manual Defrost	74	51	39	30
Frost-free	24	48	60	69
Total	98	100	100	100
Separate food freezer	23	30	38	47
Dishwasher	3	13	39	55
Clothes washer				
Wringer	19	11	7	3
Automatic	44	64	84	90
Total	62	75	89	91
Clothes dryer	24	46	70	81
Television				
Black-and-white	74	63	57	64
Color	27	48	63	74
Total	94	96	98	98
Air-conditioning				
Window	17	34	39	33
Central	4	10	19	32
Total	22	45	58	64

Source: Washington Center for Metropolitan Studies, Lifestyle and Energy Household Survey, 1972-1973.

FIGURE 5-6
Average Family Income and Percent Spent for Energy



Source: "A Time to Choose," final report of Energy Policy Project, Ford Foundation, Ballinger, Cambridge, Massachusetts, 1974.

the indirect energy used to manufacture homes, furnaces, furniture, cars, clothing, etc., and to service households. This energy is much harder to trace since there is no complete set of statistics available on the energy required to build a house or a stereo set, to print or deliver a magazine, etc. An estimate from the Ford Energy Project study is shown in Table 5-7. The four categories shown do not account for all indirect energy use. Entertainment, clothing, books, furniture, etc., are not included, nor is the energy expenditure by the government for postal services, the military, the space program, etc. Even without taking into account the uneven distribution of this additional indirect energy among income groups, the spread between total direct and indirect energy consumed by the extreme groups is already large, as shown in Figure 5-7.

There are two final points we wish to make before leaving this section on income and energy. The first is the obvious one that changes in our energy policy, in particular changes brought about through pricing, must not be designed so they increase the energy gap between rich and poor. Increasing energy's price increases the already-large percentage of income the poor pay for it. Similarly, the poor buy energy primarily for necessities — home heating and cooling, cooking, water heating, etc. Cutting back on energy use may well mean cutting into essential uses.

TABLE 5-7
Annual Indirect Energy Use Per Household by Income Groups (million Calories)

Income Group	Food	Autos	Housing	Appliances	Total
Poor	9.5	8.8	2.5	1.5	22.3
Lower Middle	16	20	2.8	1.8	40.6
Upper Middle	20	30	3.3	2.1	55.4
Well Off	24	37	4.0	2.5	67.5

Notes:
Income Group is defined in Table 5-5.

Food: Includes tractor fuel, fertilizer manufacture, container manufacture, food processing, trade, and transport.

Autos: Includes auto manufacture and support industries such as highway construction, repairs, tires, operation of service stations, and insurance companies. Allocated among the income groups according to auto ownership patterns and miles driven, from Washington Center for Metropolitan Studies Lifestyle and Energy Surveys, 1972-1973.

Housing Materials and Construction: Based on estimated energy consumption per square foot of housing, amortized over 50-year lifetime for house. Allocated among income groups according to square footage of homes, estimated from WCMS data on number of rooms.

Appliances: Total energy use for manufacturing appliances amortized over 8 years for water heaters, 14 years for all other appliances. Allocated among the income groups according to ownership data from WCMS.

Taken from: "A Time to Choose," final report of Energy Policy Project, Ford Foundation, Cambridge, Massachusetts: Ballinger, 1974, Table 78.

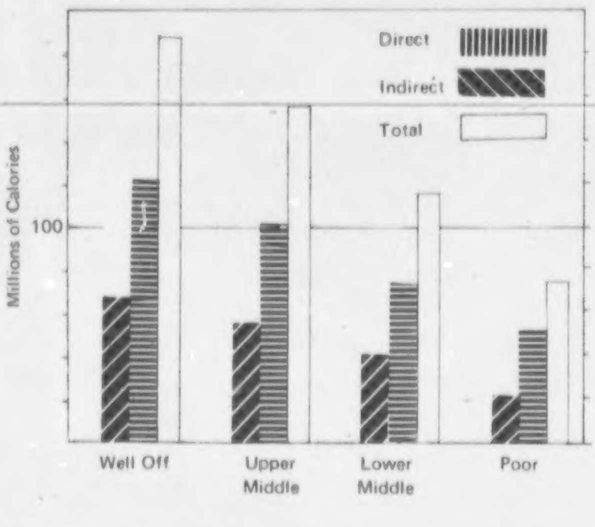
The second point comes from a comparison of direct and indirect energy. It is striking, for instance, that the 26 M Calories of food energy per year charged to the well-to-do is 7.4 times as large as the 3.5 M Calories which a family of 3.2 persons (the size of the average household in the study) would consume (at 3,000 Calories per day). What we are measuring is the inefficiency of the overall food system. It is also worth noting that the annual indirect energy charged to manufacturing automobiles, providing roads, operating service stations, etc. is almost as large as the fuel used directly to propel the car. In both these instances the upper-income brackets, because they dominate the market, set the standards which the market follows and with which the poor must live. These standards are energy-intensive ones.

Energy in Food Production

We will pick up the hint of the previous paragraph: if the energy expended in growing, processing, packaging, and transporting food is divided by the food consumed per household we find a factor of 7 or 8. What this means, at face value, is that it requires 7 or 8 Calories of fossil fuel energy to get 1 food Calorie on our plate. We are eating fossil fuels. The food crisis and the energy crisis are therefore joined.

There are several reasons why it is important that we examine our food industry from an energy point of view. It uses a significant amount of energy, 12 or 13 percent of the national total. It is important, therefore, to understand in what form and for what purposes that energy is used in order to make rational choices among the various energy futures before us. More important, however, is the worldwide food shortage and America's role as

FIGURE 5-7
Direct and Indirect Energy Use by Income Group*



*See Table 5-7 for a breakdown of indirect energy uses.

food supplier. What are the energy implications of that policy? Finally, we may want to examine our food production system as a model for others to copy. Is this system one that can meet world needs?

The energy cost of U.S. food production: How much energy does it take to put a Calorie of food before an American consumer? To answer this question it is necessary to determine the energy consumption in the four major components of the food system: the farm, the processing industry, the commercial retailing industry and the home. In each of these there are direct uses (fuel and electricity) and indirect uses (energy consumed in the manufacture of food-related equipment, or in transportation and in the manufacture of fertilizers, pesticides, herbicides, etc.).

We present in Table 5-8 the results of an energy audit of the food system from 1940 to 1970. (The source of that study is indicated on the table.) In Figure 5-8 we plot the total energy and compare it with the energy of the food produced. Figure 5-9 shows the growth in the amount of energy in each of four component sectors (see Table 5-8) which make up the total.

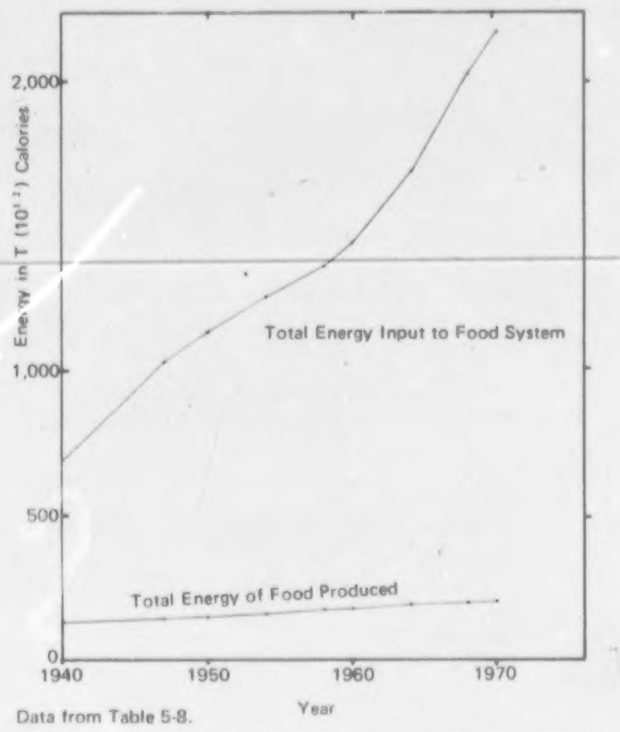
We are prepared for the comparison of Figure 5-8 by our earlier rough estimate. The ratio of the amount of energy used in the system to the number of Calories eaten by the population has grown from 5.3 in 1940 to 10.9 in 1970. Figure 5-9 shows us where this growth has occurred. Energy consumption has grown in each of the three categories but the fastest growth has been in the energy (direct and indirect) used on the farm. Over the 30-year period, total farm energy use increased by a factor of 4.2 (compared with 3.0 for food processing and 1.2 for the commercial and home sector). We can see from Table 5-8 that fuel use, electricity, fertilizer, and the energy to build farm machinery accounted for most of that growth.

It should be emphasized that even with the detail of Table 5-8 these data are still fairly rough. There is no account taken, for instance, of food wasted or the growing amount of food exported. It is certainly accurate enough, however, to raise some serious questions for the future.

If we look at the data of Figure 5-8 in a somewhat different way, and plot the food energy output against the fossil fuel energy input, we obtain the interesting curve of Figure 5-10. This looks suspiciously like the S curve we discuss in Chapter 4, Volume II. It is a curve which suggests the end of growth. It is easy for us to interpret this figure in the present context. It suggests that we cannot gain very much more food energy from our system by merely putting more fossil-fuel energy into it.

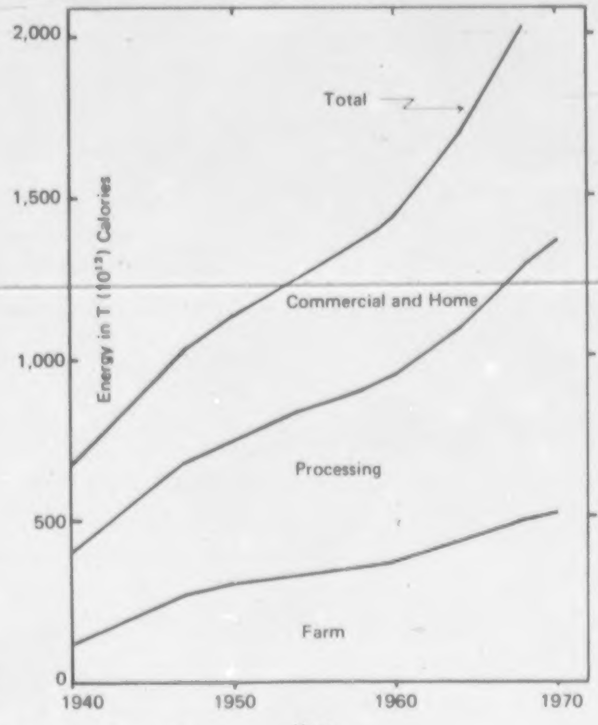
It does not say that we are farming as efficiently as possible, for we are considering all the energy used in the system and as we see in Figure 5-9, the farm energy

FIGURE 5-8
Total Energy Use in Food System Versus Calories of Food Produced (food is population times 2,700 Calories per day)



Data from Table 5-8.

FIGURE 5-9
Growth in Energy Consumption of Food System Components



Data from Table 5-8.

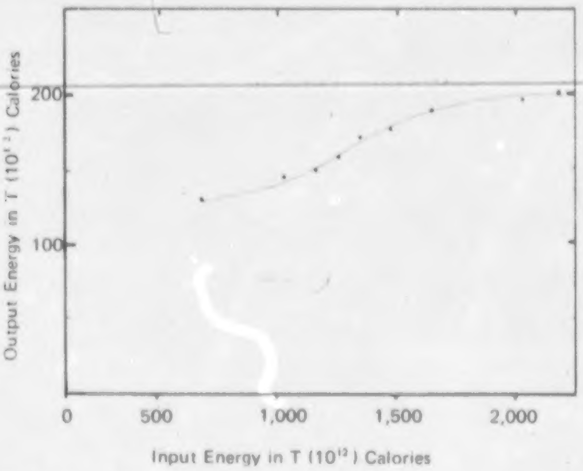
only represents a quarter of the total. From other studies,[2] however, it appears that with some crops, corn is the example quoted, we are already using 1,000 Calories of energy per square meter (farm energy alone) and achieving energy yields of 2,000 Calories of energy per square meter from the grain alone. These numbers are to be compared with 5,000 Calories per square meter of energy that the corn plants can take in from sunlight. Since the energy output is almost one-half the captured solar energy it is unlikely that we can gain much more farming efficiency by adding more fertilizers, plowing more often, using more herbicides, etc. In fact, if we look at yields per acre as tons of fertilizer applied per acre, we obtain a curve similar to the one shown in Figure 5-10. It is an S-curve and we are on the flat top. We cannot buy much more plant productivity with energy.

Agricultural practice is a deep and engrossing subject, and there is much more which could be said. There are a variety of suggestions for increasing yields without increasing acreage, by reducing fertilizer per acre and bringing such "soil bank" land as remains unused back into production, or by using more of the organic waste we produce, as land conditioners and supplementary fertilizer. We will leave that fuller discussion to others.

There are conclusions we can suggest, however, from this energy-focused consideration. The first is that food prices will rise with energy prices. They are, in fact, expected to rise more rapidly than energy since a large part of the energy input is of the indirect sort expended in manufacturing. It may be that energy costs will become high enough to make farming depart from its path of increasing capital intensiveness and make a partial return to farm labor an economic alternative.

FIGURE 5-10

Food Energy Output Versus Energy Input to Food System



Data from Table 5-8.

This energy analysis of agriculture also raises questions as to the wisdom of continuing in the direction of food "mass production" practices. We question it from our own point of view; it has not proven to be an energy-efficient way to feed our own people (although it has been labor-efficient, and so far capital-efficient). It is even less attractive as a way to feed the world's hungry people. As it is now practiced, we are exporting energy when we export grain, 5 or 10 Calories for every food Calorie it contains. That is not a wise strategy for an energy-importing country.

It is an even more questionable decision to consider exporting our agricultural practices. We are engaged in that at present. The so-called "Green Revolution" is based on new strains of high-yield grains, but these new grains require both fertilizer and irrigation. As we see from Table 5-8 both of these are energy expensive. (The irrigation energy expenditure in Table 5-8 is based on irrigation of only 5 percent of our crop land.)

We may in fact have something to learn from foreign agricultural practices. By relying on human labor some other countries get many more Calories from the earth and sunlight than they put in. The Chinese peasant gets 50 Calories of food energy back for every 1 he expends on his wet rice fields. The primitive "slash and burn" agriculture of the tropics, in which a new field is cleared of trees every two or three years, gains Calories in almost a 20 to 1 ratio.

We are, of course, not prepared to become a nation of farmers again in order to save some of the energy used in farming. Somewhere, in the chain of energy conversions from farm to table, careful analysis should turn up some uses which could be omitted. The growing of plants, after all, should be an energy-producing activity fueled by the always abundant energy of the sun. Our fossil fuel Calories are becoming too expensive to eat.

Financing Energy Growth and Environmental Protection

In our analysis of the energy supply-and-demand picture for the next decade or so (Chapter 5, Volume II), we included among the necessary supplies the investment capital needed to explore for oil, build ports and tankers, open new coal mines, etc. A summary of the billions of dollars needed under various supply scenarios is given by Table 5-4, Volume II. The totals range from $451 billion (1970 dollars) for the case which projected high oil imports to $547 billion for the all-domestic case. If we deduct from these National Petroleum Council estimates those amounts of capital that were used to finance items which can be deducted from profits before taxes (and thus cost nothing); the average of these four cases of Table 5-4 is $380 billion. This amount is to be split among the various energy needs as shown in Table 5-9.

In this section we will examine these financial needs and ask whether this money can be raised or whether a lack of investment capital in the next four years might limit energy growth. We will rely, in this discussion, on the analysis of financial constraints provided by the FEA Project Independence Report.

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[2] "Food Production and the Energy Crisis," Pimentel, Hurd, Bellotti, Forester, Oka, Sholes, Whitman, **Science 182,** 443-449, November 2, 1973.

The question of the availability of investment money can only be answered with reference to the past. Since World War II, investment in the energy-producing industries (coal, oil, gas, uranium, and the utilities) has ranged between 20 and 25 percent of total business investment. The capital market should, therefore, be able to handle future demand from the energy industry if it falls within that percentage range of the expected total investment money.

We must therefore look to the future, to expected growth in the GNP and in business investment, to see whether 20 or 25 percent of the expected totals are large enough to meet the projected needs. The projections of available dollars range from a low of $366 billion to a high of $502 billion. The conclusion is that the money will be available even for the FEA "Accelerated Supply Case" of Table 5-9.

Trouble at the utilities: The details of the FEA study are optimistic for oil and gas and for coal (where the total amount is low and the oil companies are expected to invest heavily). The investment picture for the utilities, however, is not as bright.

As we see from Table 5-9, the utilities will need to raise something between $186 billion and $315 billion in order to begin construction of the nuclear and coal-fired plants and transmission lines needed in the next 10 years if they are to meet expected electric power demand. The record this year has not been very encouraging. Some 70 plants which were to have been started have been delayed or abandoned.

The major reasons for the uncertainty making utility investment unattractive, at least at the moment, have already been discussed. The conservation efforts by power company customers have been extremely successful and cash flows (and dividends) have been lowered. The air quality criteria have put fuel supplies, especially coal, into question. The performance of the bigger units (of about 1,000 Mw), especially the nuclear ones, has been erratic — they have operated on the average at considerably less than the expected 75 percent capacity.

A final note of uncertainty is entered by the demand projections themselves. As we said in Chapter 1, the growth rate of electric energy, which has been 6 or 7 percent per year for 20 years or so, dropped below 1 percent this year. It is not clear as yet whether this was a short-term response by the public or whether some

TABLE 5-8

Energy Use in the U.S. Food System (in 10^{12} Calories)

Component	1940	1947	1950	1954	1958	1960	1964	1968	1970
				On Farm					
Fuel (direct use)	70.0	136.0	158.0	172.8	179.0	188.0	213.9	226.0	232.0
Electricity	0.7	32.0	32.9	40.0	44.0	46.1	50.0	57.3	63.8
Fertilizer	12.4	19.5	24.0	30.6	32.2	41.0	60.0	87.0	94.0
Agricultural Steel	1.6	2.0	2.7	2.5	2.0	1.7	2.5	2.4	2.0
Farm Machinery	9.0	34.7	30.0	29.5	50.2	52.0	60.0	75.0	80.0
Tractors	12.8	25.0	30.8	23.6	16.4	11.8	20.0	20.5	19.3
Irrigation	18.0	22.8	25.0	29.6	32.5	33.3	34.1	34.8	35.0
Subtotal	**124.5**	**272.0**	**303.4**	**328.6**	**356.3**	**373.9**	**440.5**	**503.0**	**526.1**
				Processing Industry					
Food Processing Industry	147.0	177.5	192.0	211.5	212.6	224.0	249.0	295.0	308.0
Food Processing Machinery	0.7	5.7	5.0	4.9	4.9	5.0	6.0	6.0	6.0
Paper Packaging	8.5	14.8	17.0	20.0	26.0	28.0	31.0	35.7	38.0
Glass Containers	14.0	25.7	26.0	27.0	30.2	31.0	34.0	41.9	47.0
Steel Cans and Aluminum	38.0	55.8	62.0	73.7	85.4	86.0	91.0	112.2	122.0
Transport (fuel)	49.6	86.1	102.0	122.3	140.2	153.3	184.0	226.6	246.9
Trucks and trailors (manufacture)	28.0	42.0	49.5	47.0	43.0	44.2	61.0	70.2	74.0
Subtotal	**285.8**	**407.6**	**453.5**	**506.4**	**542.3**	**571.5**	**636.0**	**787.6**	**841.9**
				Commercial and Home					
Commercial Refrigeration and Cooking	121.0	141.0	150.0	161.0	176.0	186.2	209.0	241.0	263.0
Refrigeration Machinery (home and commercial)	10.0	24.0	25.0	27.5	29.4	32.0	40.0	56.0	61.0
Home Refrigeration and Cooking	144.2	184.0	202.3	228.0	257.0	276.6	345.0	433.9	480.0
Subtotal	**275.2**	**349.0**	**377.3**	**416.5**	**462.4**	**494.8**	**594.0**	**730.9**	**804.0**
Grand Total	**685.5**	**1,028.6**	**1,1134.2**	**1,251.5**	**1,361.0**	**1,440.2**	**1,690.5**	**2,021.5**	**2,172.0**

Source: "Energy Use in the U.S. Food System," C. Steinhart and J. Steinhart, Science 184, 307-315, 1974, Table 1.

deeper adjustment is taking place. The decisions here are complicated by the size of the financial commitment needed for an individual plant and the time that it takes to build one.

The relevant data on which these decisions rest are summarized in Table 5-10. The fuel costs favor the nuclear plant followed by the coal plant. The operating and maintenance costs also favor the nuclear plant. The question that must be answered, however, has to do with the capacity level at which the plant will operate and the time it will take to get the plant into operation. Operating at 70 percent capacity, the nuclear plant is expected to provide the least expensive electricity followed by coal, oil, and gas. At 40 percent capacity the coal plant is the choice. At 10 percent capacity the order is almost reversed from the high-capacity case; it is gas, coal, oil, and nuclear.

What the utilities fear is the following chain of events. Projecting growth at the traditional rate (demand doubling every 10 years) they choose to build a big nuclear (or coal) plant. They ask for and receive the rate increases necessary to enable them to attract the capital to build the plant and they begin the seven to 10-year job of planning and building. Due to rate increase, however, demand does not grow as rapidly as projected and when the plant comes on line its full capacity is not needed, it is forced to run at lower capacity, the cost of the electricity it produces is higher than estimated, and the vicious circle continues. In this atmosphere of uncertainty the temptation is to choose the gas turbine which can be built quickly and relatively cheaply, but which will produce more expensive electricity and will be threatened by a shortage of natural gas.

TABLE 5-9
Cumulative Capital Requirements for Energy Production, 1975-1985 (in billions of 1973 dollars)

Industry	NPC Projection(a)	FEA Accelerated Supply(b)
Oil and Gas (incl. refining)	133	98.4
Coal	8	11.9
Synthetic Fuels	10	0.6
Nuclear	7	138.5
Electric Power Plants (excluding nuclear)	137	60.3
Electric Transmission	42	116.2
Transportation	43	25.5
Other (solar, shale, waste treatment, etc.)	0	2.2
Total	**380**	**454**

Source: Project Independence Report, Federal Energy Administration, 1974, Table V-21.

(a)Average of the four supply cases of Table 5-4, Chapter 5, Volume II, with $107.4 billion of deductible outlays subtracted.

(b)This is the FEA option which is the most optimistic as far as domestic supplies are concerned.

We are in the midst of the decision-making time. There are interesting lessons on the operation of our capital markets to be learned. The result of the decisions will have an impact throughout the energy web; all the way from the plains of North Dakota to the electric bill in the nearest mailbox.

Paying for Pollution

Among the new costs of energy in the next ten years will be the dollars needed to prevent continued degradation of the environment. The Council on Environmental Quality (CEQ), in its fourth annual report (1973), summarized these costs under four headings: *damage* costs, due to illness and property damage; *avoidance* costs, which include such costs as the expense of traveling further to find a clean swimming beach; *transactional* costs, the cost of making and enforcing regulations, and *abatement* costs, to reduce pollution through sewage treatment plants or emission control devices.

The major costs are abatement costs, for control of particulates and SO_x, for control of automobile exhaust, and for water pollution and solid waste. The CEQ summary of these total costs is given in Table 5-11. The responsibility for these expenditures is expected to be shared between the public and private sectors, as shown in Figure 5-11.

The cumulative total overall pollution cost categories for the period 1977-1981 is projected to be

TABLE 5-10
Comparison of Costs of Power Generating Plants (M Kw-hr at the generating plant)

	Nuclear	Coal	Oil	Gas Turbine
Fuel Cost	2.50	5.56#	15.83#	23.54
+O&M	1.50	2.75	2.65	2.50
*Fixed Charge				
Capacity (.7)	14.84	11.48	10.45	5.12
Factor** (.4)	25.97	20.10	18.30	8.96
(.1)	103.88	80.37	73.18	35.84
Total Cost				
Capacity (.7)	18.84	19.79	28.93	29.88
Factor (.4)	29.97	28.41	36.78	32.76
(.1)	107.88	88.68	91.66	52.93
+Plant Cost $ per kw	455.00	352.00	320.00	117.80
Years to Build	10	7	7	2

Source: Project Independence Report, Federal Energy Administration, 1974, Table V-24.

*Fixed charges are those costs associated with depreciation, interest, return on equity, State and local taxes plus Federal income tax and are assumed to be 20 percent of plant cost.

**The fraction of maximum capacity in use.

#Fuel costs are $14.52 per ton for coal, $10.59 per bbl for residual oil used in the oil turbine, and $11.77 per bbl for distillate used in gas turbines.

+Operation and maintenance including environmental costs.

$274.2 billion. The largest energy-related share of this is the $105.6 billion from air pollution, although $1 billion from radiation and $4.5 billion from surface mining must also be added.

These amounts of money are large, but the costs of the damage they are designed to prevent are also large. The $11.3-billion estimate for air pollution control in 1971 must be compared with the $16.1 million estimated damage from air pollution in 1968. The large costs when considered from this viewpoint are a good investment.

Who pays: As we see from the breakdown of Figure 5-11, it is anticipated that the private sector will pay two-thirds of the bill. There is concern, however, that these costs may be spread in an inequitable fashion through the income distribution of our society. It will be unfortunate if they are loaded on the backs of the poor, for they do not stand to benefit as much from many of the control measures as do the rich. They do not, for instance, use recreational facilities as much as the rich. Air pollution abatement, however, will benefit the inner-city residents, for pollutant levels are higher there than in the suburbs.

Generally speaking the government expense collected through taxes will come in greater proportion from the upper income-brackets. Private expenditures, however, are likely to be added to the cost of basic energy goods and services. Since, as we have seen, the poor pay a larger share of their income for energy than do the rich, they will also pay a slightly larger share of

TABLE 5-11
Estimated Total Pollution Control Costs (in billions of 1972 dollars)

Pollutant/medium	1971			1981			Cumulative—1972-81		
	O&M[1]	Capital Costs[2]	Total Annual Costs[3]	O&M[1]	Capital Costs[2]	Total Annual Costs[3]	Capital Invest-ment	O&M[1]	Total Annual Costs[3]
Air Pollution									
Public	0.2	<.05	0.2	1.0	0.2	1.2	1.4	7.1	8.4
Private									
Mobile[4]	1.1	<.05	1.2	6.2	4.3	10.5	27.1	39.1	58.8
Stationary	.4	.3	.7	4.2	1.5	5.7	11.4	27.0	38.4
Total	**1.7**	**.3**	**2.1**	**11.4**	**6.0**	**17.4**	**39.9**	**73.2**	**105.6**
Water Pollution									
Public									
Federal	.2	NA	NA	.2	NA	NA	1.2	2.8	NA
State and Local	1.2	3.8	5.0	2.6	7.0	9.6	47.2	20.0	76.9
Private									
Manufacturing	.4	.3	.7	2.2	1.5	3.7	12.3	15.8	27.5
Utilities	.2	.1	.3	1.6	.9	2.5	6.8	10.9	16.5
Feedlots	0	0	0	<.05	<.05	<.05	.2	<.05	.2
Construction sediment[5]	<.05	NA	NA	<.05	<.05	<.05	.3	<.05	.2
Total	**2.0**	**4.2**	**6.0**	**6.6**	**9.4**	**15.8**	**68.0**	**49.5**	**121.3**
Noise									
Commercial jet aircraft	NA	NA	NA	NA	NA	NA	(.4-1.6)	NA	NA
Radiation									
Nuclear powerplants[6]	NA	NA	NA	<.05	.2	.2	1.2	<.05	1.0
Solid waste									
Public	1.0	.2	1.2	1.7	.4	2.1	2.6	13.8	16.3
Private	2.0	<.05	2.0	3.1	.1	3.2	.3	25.2	25.5
Total	**3.0**	**.2**	**3.2**	**4.8**	**.5**	**5.3**	**2.9**	**39.0**	**41.8**
Land reclamation[7]									
Surface mining	NA	0	NA	.8	0	.8	0	4.5	4.5
Grand Total[8]	**6.7**	**4.7**	**11.3**	**23.6**	**16.1**	**39.5**	**112.0**	**166.2**	**274.2**

Source: **Environmental Quality 1973**, Council on Environmental Quality (Washington: USGPO) 1973.

[1] Operating and maintenance costs.
[2] Interest and depreciation.
[3] O&M plus capital costs.
[4] Excludes heavy-duty vehicles.
[5] Includes only sediment control for housing and highway construction.
[6] Radiation figures include incremental costs only. The total costs of radiation control are inseparable from other costs of building and operating a nuclear powerplant.
[7] Land reclamation costs are assumed to be current expenditures.
[8] Does not include noise control.

pollution expenses. This is an inequity which must also be taken into account by energy policy planning.

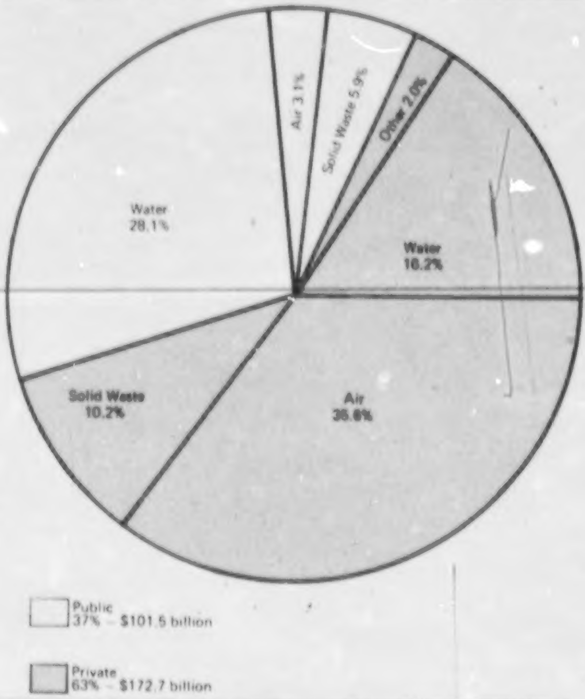
The general worry that investment for pollution control will retard the economy and drive prices sky high seems to have been mitigated by the results of the most recent CEQ study. In a recent news release[3] it was reported that only 2 percent of the firms sampled claimed that investment in pollution control had displaced any of their planned investments for modernization or expansion. It also reported that the results of four separate analyses indicate that pollution control expenditures were responsible for only one-half of 1 percent of the 17 percent increase in the wholesale price index from 1973 to 1974. (This is to be compared to the rise in the price of energy which contributed a third of the total increase.) We can, apparently, afford pollution control.

Summary

In this chapter we looked at some of the relationships between energy and another of the big Es, the economy. The energy web, of course, reaches into all parts of our economic system and we tried to select sectors to examine that either were crucial to our well-being or interesting (or both).

FIGURE 5-11

Distribution of Total Environmental Expenditures, 1972-1981[1]



Source: "1973 Environmental Quality," Council on Environmental Quality

[1] Figures do not total due to rounding.

We found that there was at least a rough correspondence between high energy consumption and a large GNP, both in international comparisons and in our own historical record. We found further that the efficiency with which energy produces a dollar of GNP had been rather steadily increasing over the past 20 or 25 years (the ratio of Calories to GNP dollars has been decreasing). In the late 1960s, however, that increase stopped and the ratio of Calories to GNP dollars increased. We were left with some uncertainty as to the long-range trend.

The predictions in the energy-employment area were somewhat easier to make. Although a sharp decrease in available energy (as occurred during the embargo) would have serious effects, changes over longer time-frames should have little effect if properly anticipated. The energy-producing industries and the industries which use large amounts of energy are "capital-intensive" and do not employ a large percentage of the nation's workers.

We examined the relationship between energy consumption and income and found that energy like wealth is inequitably distributed in this country. The danger of the present trend is that increasing energy prices will widen the energy gap.

We used this chapter to examine briefly another troublesome part of the energy web, the energy needed by the food system. What we found on analysis is that year by year the number of Calories that must go into the system in order to get a food Calorie out is now about 10, and growing. The food crisis and the energy crisis are thus firmly joined.

The final discussion was of the $380 billion in capital needed to assure the anticipated expansion of the energy supply. All projections seemed reassuring as far as the total is concerned. We are, however, in the midst of the moment of decision for the utilities companies as they search for investment capital and begin to move their next big plants off the drawing boards.

We only looked at segments of the economy in this chapter. The Source Book itself is not big enough to consider all of the interlacings between these two Es. The most important conclusion we can draw from those aspects of the system we did examine is that careful planning is needed. We have crossed a new frontier into an era of expensive energy; the familiar landmarks are gone. We can continue our journey only with a carefully drawn map. The making of that map, the construction of an energy policy, will be the subject of the concluding chapter of this Source Book. In the next chapter we will look at a set of modifications that should be a part of any energy policy: strategies for energy conservation.

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[3] News release, Council on Environmental Quality, December 9, 1974.

CHAPTER 6
Prospects and Strategies For Energy Conservation

Prospects and Strategies For Energy Conservation

"Turn out the light when you leave the room." "Shut the door, were you born in a barn?" These once familiar phrases from a conservation oriented past have rarely been heard, or at least rarely attended to, by the under-thirty generation. The energy crisis may bring them back into vogue.

In the two volumes of this Source Book, we have documented and described the multidimensional problem which we abbreviate as "the energy crisis." We have examined consumption, its growth, and the problems of supply and demand which accompany this growth. We have looked at changes in the economic sector, and in other sectors of society, which were marshalled in by this era of high-priced energy. In the earlier chapters of this volume, we have examined the impact of the production, transportation, and consumption of energy on the environment and on man as a part of that environment. In Volume II, Chapters 6 and 7, we look beyond the present at some of the technological advances that might ease the crisis.

There are many suggestions in these volumes of ways to improve this or that aspect of the energy crisis. If we look at any individual piece of it, at the environmental impact of coal mining, or the danger of plutonium 239 theft, or the shortage of investment capital, we can devise a "cure." There are very few of these "cures," however, that have general application. The message that cries out from analysis after analysis, and the response which could have the most immediate and positive impact on the widest range of problems, is a simple one. We must use less energy.

It will take four or five years at the minimum to open enough coal mines, build enough refineries, drill enough wells, or float enough new tankers to begin to make a dent in the supply-demand problem. This country demonstrated, however, in the five or six months of the oil embargo, that we could immediately implement procedures to significantly reduce our consumption of fuel oil, gasoline, and electricity.

The data on energy consumption in 1974 give us some concrete evidence on which to base our expectations of the savings which could be effected. In 1974, for the first time since 1952, total energy consumption decreased. After rising at an average annual rate of 4.1 percent since 1960, consumption fell by 2.2 percent, from 18.9 Q Calories to 18.5 Q Calories.

The reduction in the consumption of electricity was particularly startling. After two decades of growth at an annual rate of almost 7 percent, electric consumption fell in 1974 by 1.9 percent, from 1.495 T kilowatt-hours in 1973 to 1.466 T kilowatt-hours.

Even more impressive was the cutback in oil consumption from 6.317 B bbls (billion barrels) in 1973 to 6.080 B bbls in 1974. This reduction averages out to 815 M bbls per day which is almost equal to the 1 M bbls per day which is the targeted figure for Administration conservation strategies. Unfortunately, in spite of the overall reduction and the oil embargo, the amount of crude oil imported in 1974 rose by 7 percent, from 1.18 B bbls to 1.27 B bbls.

The reductions in consumption were not all due to specific conservation measures, voluntary or enforced. The recession, the embargo, and the mild winter all played important roles. There is no doubt, however, that the rise in the price of energy, which is itself a suggested conservation tactic, was an important contributor to the savings.

It is of interest to look at the savings in electrical energy in terms of fuel. In 1973 the primary energy for electric generation came from coal, 43.5 percent, oil, 18.5 percent, and natural gas, 18.6 percent. Hydropower contributed 15.0 percent and nuclear reactors, 4.5 percent. In 1974 the percentages were coal, 44.1 percent; oil, 16.9 percent; natural gas, 17.6 percent; hydropower, 15.4 percent, and nuclear, 6.0 percent. Coal use increased by 2.3 M tons, while oil used was reduced by 34.7 M bbls and natural gas use reduced by 0.34 TCF (trillion cubic feet).

The environmental impact of these changes from 1973 to 1974 is also interesting. The increase in coal demand by the utility industry led to the strip mining (at 10,000 tons per acre) of perhaps 230 additional acres. For the United States as a whole, however, coal consumption decreased by 16.5 M tons. If half this came from strip mining, the energy savings translate into 800 fewer acres of strip mined land. In spite of the utilities reduction in oil use, the overall increase in imported oil of 84.7 M bbls required an additional 102 trips by supertankers of Torrey Canyon size and we can expect statistically that 0.1 percent of this imported oil, 84,700 bbls, was spilled. The reduction in oil and gas consumption overall led to a reduction in air pollution. The 16.5 M tons of coal not burned reduced the sulfur oxide pollution by perhaps 3.2 M tons and reduced expected mining deaths by 4, and so on.

Even these specific ripples, which spread from the reduction in energy consumption, do not exhaust the results. We could also compute the dollars saved by the consumer in not buying this energy and balance it against the wages lost by workers in energy-limited industries.

Taken all together these several results provide strong support for those who urge this country to choose, as its major energy policy theme, a deliberate, carefully planned program of energy conservation. No other policy option can produce results so rapidly, and no other option impacts so positively on the broad spectrum of energy-related problems.

With this general justification for such a policy, we will devote this chapter to a survey of the most promising targets for conservation strategies and to an analysis of some of the mechanisms, economic and political, for implementing them.

Less May Be More

There are two somewhat different approaches we can take in order to save energy. We can tighten our belts and use less energy, drive fewer miles in our cars, turn off lights, turn down thermostats, take shorter showers, etc. In other words, we can move to a less affluent lifestyle. We can also use less energy by improving energy productivity, by getting more useful heat and work from each extracted Calorie of primary energy. By an emphasis on improving energy productivity, by improving the efficiency with which we convert it to our use, we may be able, with less per capita energy expenditure, to live as well or better. Less may be more.

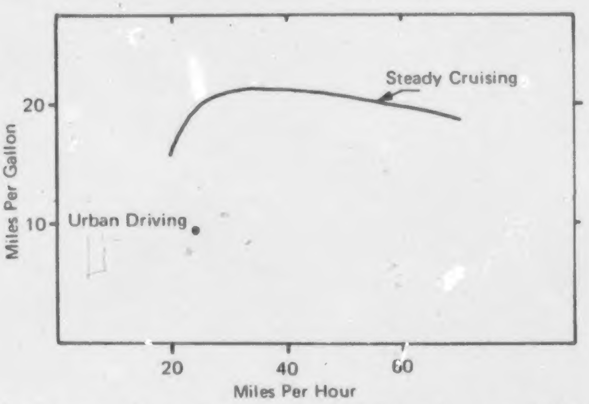
It is likely that we will have to use both strategies, at least in the beginning. The belt-tightening approach can be implemented most rapidly, it requires for the most part changes in personal practices rather than changes in physical equipment and industrial or political processes. The attack on energy inefficiency can provide the more solid, long-term gains.

Short-term Responses

It is well to look briefly at some of the most obvious and practical of the belt-tightening strategies. We have behind us some experience (and data) collected by virtue of the oil embargo. The short-term strategies were almost all targeted to the individual consumer. This target is recommended, as we have said, by the promise of quick implementation.

The major effort of conservation during the embargo was aimed at automobile transportation and home heating. These are large targets. Private automobiles consume half of the energy used in transportation and 28 percent of all the petroleum we burn (1972 data). Almost three-quarters of the energy used in the residential sector (2.3 Q Calories out of the 1972 total United States consumption of 18.2 Q Calories) was used in residential heating.

FIGURE 6-1
Effect of Speed on Fuel Economy



Data Source: EPA, "A Report on Automotive Fuel Economy," 1974.

Gasoline consumption was attacked in two ways. The highway speed limits were lowered to 55 miles per hour (MPH), and gasoline stations were closed on Sundays. The justification of the former is given by the data of Figure 6-1. Automobiles get better gasoline mileage at lower speeds. A drop from 70 MPH to 50 MPH, for instance, increases gasoline mileage by about 20 percent. Actual savings are, of course, lower than this; 5 percent was the Department of Transportation estimate, since automobiles don't go a steady 70 MPH.

The expected savings from the Sunday sales ban was to come from reducing the 25 percent of total mileage that was accumulated in weekend driving. The modest goal was a 10 percent saving, and the two strategies together were expected to save 1 M bbls of oil per day.

The short-term goal of saving energy by lowering home comfort levels was based on the following experience. The rate at which heat leaks through a barrier depends on the temperature difference. Less heat is lost in the winter (and less cooling needed in the summer) if the inside/outside temperature difference is decreased. In the average American home, a one-degree change in the thermostat setting (up in the summer, down in the winter) reduces fuel consumption by 3 to 4 percent. A 5°F change in daytime "comfort temperature" and a 10°F change at night should produce an estimated 15 to 20 percent fuel saving. These energy saving techniques, of course, also save money.[1]

These are the easy strategies as far as their implementation is concerned (although enforcement might be difficult). From the embargo experience and from the numerous energy studies that have taken place during the past year, the Federal Energy Administration (FEA) has developed a more elaborate repertoire of short-range strategies, which is shown in Figure 6-2.

Figure 6-2 is a mixture of easy and difficult strategies as far as lifestyle disruption is concerned. All of them could, in theory, be turned on rapidly (the FEA estimate, as we see from this figure, is 60 days to completion). The three emergency measures we have just discussed are shown along with some important newcomers.

The savings are given in terms of million barrels of oil per day, since oil is the sensitive energy form. They can be converted to Calories using the data of Table 1-3 of Volume II: 1 barrel of oil = 1.5 million Calories; therefore, 1 M bbls = 1.5 trillion (T) Calories. The importance of the savings can also be judged by comparing them with the approximate 20 M bbls per day of oil consumption in 1974 and to the 6 to 8 M bbls per day of that which was imported.

Figure 6-2 gives us a strong clue to targets for our longer-range strategies. The big savings come from improving the efficiency of transportation. These are followed by savings obtained through belt-tightening in the comfort area, reductions not only in heating and cooling energy, but also in that used for lighting.

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[1] The embargo period produced several "how to save energy" booklets. The best of these are referenced in Section IV of the Energy-Environment Materials Guide.

With this as preview, let us now turn to a consideration of energy efficiency and some ways to improve it.

Long-range Strategies—Improving Energy Productivity

In order to identify our targets clearly, we look again at the energy flow diagram of Chapter 3, Volume II, which we show again as Figure 6-3. These data are from 1971 and the absolute values have changed. The 1974 comparable total (minus raw materials made from energy fuel) was 17.1 Q Calories. The percentage distribution, however, is roughly similar.

The targets stand out. Of the 4.3 Q Calories used by transportation, 3.8 Q Calories were wasted, 2.7 out of 4.9 Q Calories were wasted in industry and 1.1 out of 4.1 Q Calories were wasted in the residential and commercial sector. Another prime target is the generation of electricity; 2.5 out of 3.9 Q Calories are lost there. Our strategies, therefore, have the highest potential of return in transportation and industry, but we will not neglect the residential and commercial sector because we expect to find some easy targets there. In all sectors we will look for ways to reduce the consumption of electricity. Every kilowatt hour we turn off at the point of consumption saves 2 kilowatt-hours equivalent of primary energy back at the plant.

Energy Efficiency in Transportation

With an efficiency of utilization (see Figure 6-3) of about 12 percent and an appetite that accounted for a quarter of our total energy in 1973, transportation is a fat target.

There are two basic purposes to transportation: to move people and to move things. We will also break it down for our study into two further categories, intercity transport (trips greater than 100 miles) and urban transport. This gives us four categories: urban passenger transport (UPT), intercity passenger transport (ICPT), urban freight transport (UFT), and intercity freight transport (ICFT).

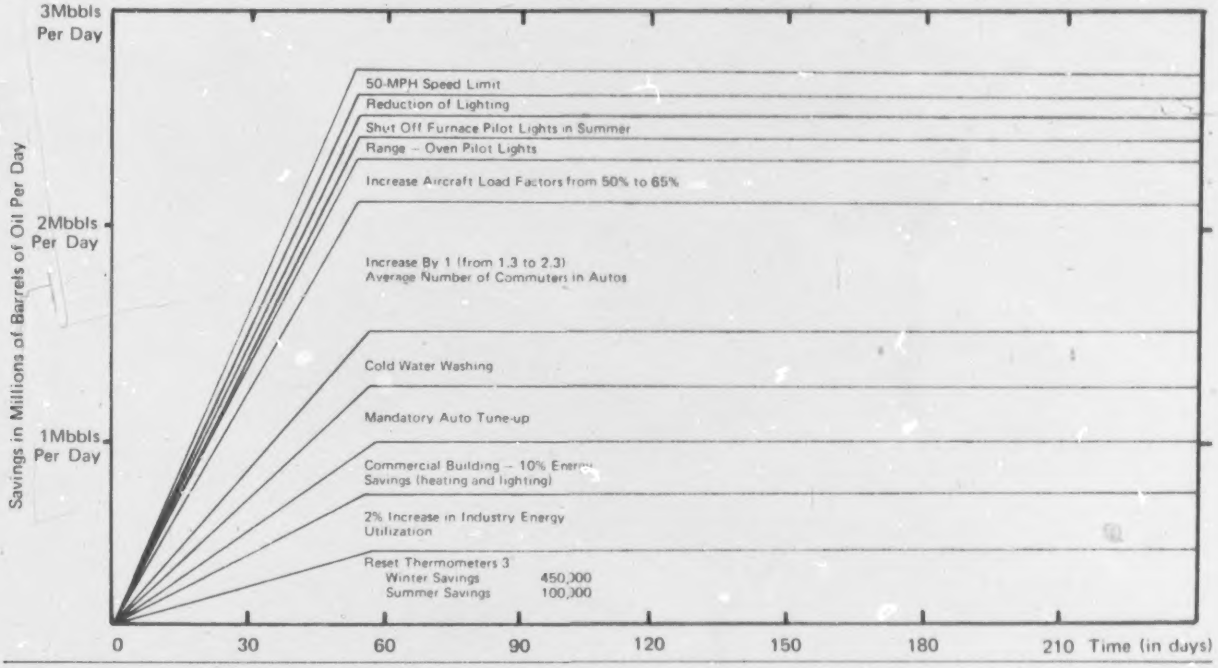
We examined the historical record of energy consumption in these four categories in Chapter 3, Volume II (Figure 3-4). Let us now examine the efficiency with which that energy is used.

Moving people: The job of moving people consumes 60 percent of transportation's total energy. As we see in Figure 3-4 of Volume II, urban passenger transport (UPT) uses about 40 percent more energy than intercity passenger transport (ICPT). In Figure 6-4, we compare the total passenger miles traveled in the two forms. Here the picture is reversed, ICPT accounts for 60 percent more passenger miles than UPT. This provides a hint of inefficiency.

A second suggestion can be formed by looking closely at the growth of the two curves. Energy use is

FIGURE 6-2

Potential Energy Saving of Emergency Conservation Programs (assuming complete 100% cooperation)



Source: "Project Independence Report," Federal Energy Administration, November 1974, Figure 1-1.

increasing more rapidly than passenger-miles. (This is consistent with the decline in automobile miles per gallon which we showed in Figure 3-10, Volume II.) We are driving more miles each year but getting fewer miles per gallon.

There are several strategies which could be used to improve the efficiency with which we move people. We could improve engine efficiency, we could increase load factors (put more people in each car, bus, or airplane), or we can switch from low to high-efficiency modes.

In order to compare the efficiency of the various modes of passenger transport, we need to define a more meaningful measure than miles per gallon. We choose what we call "energy intensiveness" (EI), which for passenger transport is in Calories per passenger mile. We show in Figure 6-5 a comparison of the EI for a number of modes of passenger transport. We see a great range of EIs from the loaded VW microbus to the yacht. We also see a pattern in which speed and convenience bring inefficiency (higher EIs). Here as elsewhere, "haste makes waste." What is also instructive is to look at the historical record of the change in the EIs of the important passenger modes of travel. These are shown for ICPT and UPT in Figure 6-6.

From the data we have now assembled, we see something of the problem and some suggestions for cures. All EI's except that of the railroad have been increasing. (The switch from steam to diesel improved railroad efficiency.) The final comparison needed is of the percentages of the passengers carried by the major transport modes. This comparison is given in Figure 6-7. In both cases, the high EI modes are increasing at the expense of the low EI modes. Air travel is increasing in importance in ICPT (rising from 2 to 10 percent) while bus and rail traffic decline. The automobile takes over from the bus in UPT.

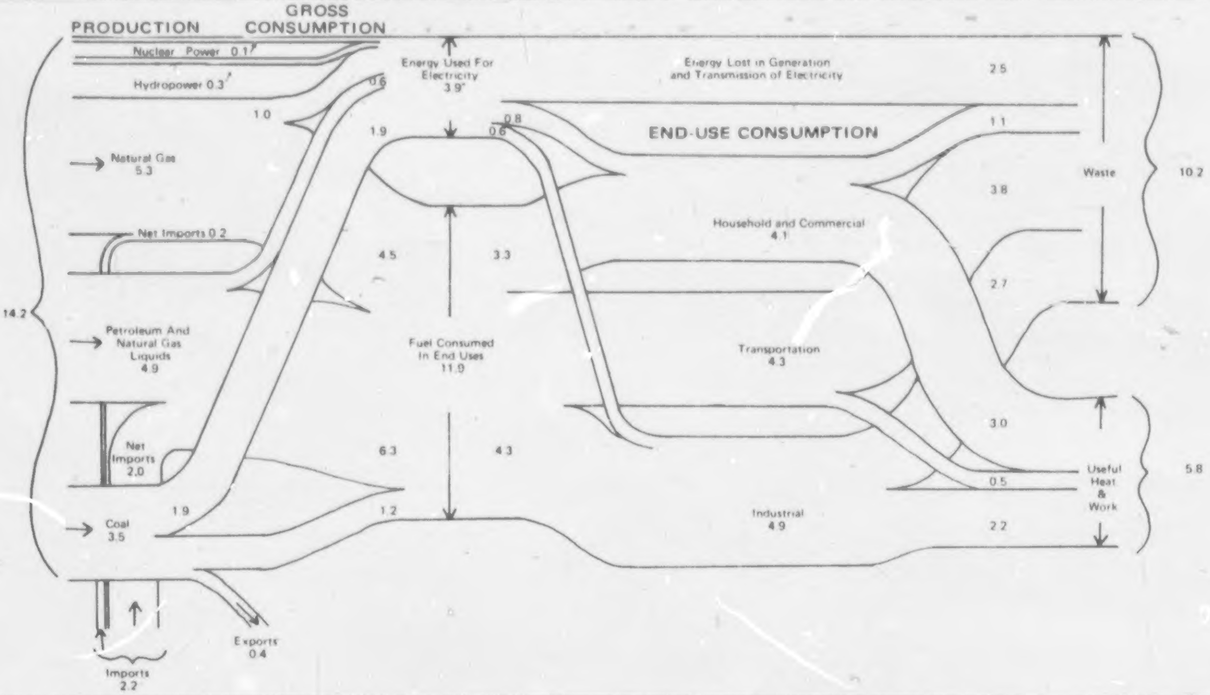
We could, therefore, cut down on energy use in transportation by improving (lowering) the EI of the dominant mode (the automobile), by improving its engine efficiency, by shifting people from automobiles and airplanes to buses or trains, or by increasing the load factors (the percentage of capacity carried) of transport modes. Let us look briefly at potential savings from these possibilities.

Switch from high to low EI modes: We show in Table 6-1 the benefits of some rather modest shifts of passengers from high to low EI modes. Of particular interest is the shift from automobiles to walking or bicycling. Both of these latter modes are essentially zero EI, they use that human energy we can usually afford to expend. We show, in addition to savings per billion passenger miles and total savings at 1970 levels of operation, the percentage of the 1970 energy consumption which could have been saved. It amounts to a respectable 2.2 percent.

Increasing load factors: We could reduce energy consumption in transportation by increasing the load

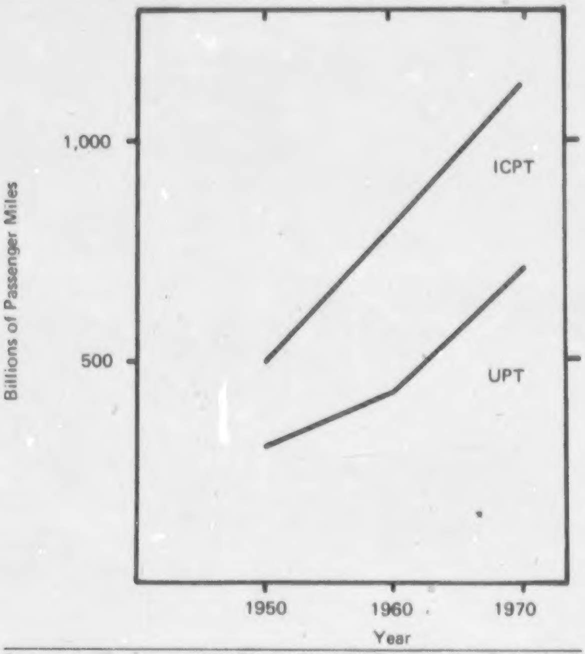
FIGURE 6-3

Approximate Flow of Energy Through the United States Economy, 1971, in Q (10^{15}) Calories


PRODUCTION
GROSS CONSUMPTION
Nuclear Power 0.1
Hydropower 0.3
1.0
Natural Gas 5.3
Net Imports 0.2
14.2
Petroleum And Natural Gas Liquids 4.9
Net Imports 2.0
Coal 3.5
1.9
Imports 2.2
Exports 0.4
0.6
Energy Used For Electricity 3.9
1.9
4.5
Fuel Consumed In End Uses 11.9
6.3
1.2
0.8
0.6
3.3
4.3
Energy Lost in Generation and Transmission of Electricity
END-USE CONSUMPTION
Household and Commercial 4.1
Transportation 4.3
Industrial 4.9
2.5
1.1
3.8
2.7
3.0
0.5
2.2
Waste
Useful Heat & Work
10.2
5.8

Source: Earle Cook, Texas A&M University

FIGURE 6-4
Passenger Miles Traveled in Urban Passenger Transport (UPT) and Intercity Passenger Transport (ICPT)



Source: "Transportation Energy Use and Conservation Potential," Eric Hirst, **Science & Public Affairs, XXIX (36)** November 1973.

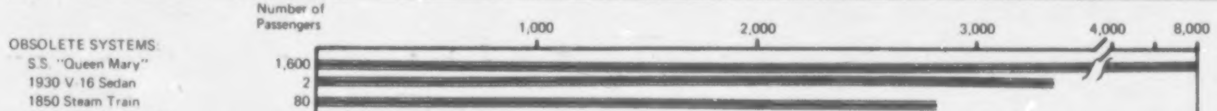
factors. For automobiles in UPT, for instance, the load factor is 28. This means that on the average a 5-passenger car carries 28 percent of its capacity (1.4 persons).

Increasing average load factors is the goal of propaganda for car pooling. A 10 percent increase in the UPT load factor, from 28 to 38 percent (from 1.4 to 1.9 persons per car), would reduce the average EI for the urban automobile (see Figure 6-6) from 2,050 Calories per passenger mile to 1,525 Calories per passenger mile. At the 1970 level of urban travel — 690 billion passenger miles — this small change would have saved 0.36 Q Calories of energy — 8.8 percent of the total transport energy.

Significant savings could be attained in ICPT by increasing the load factors in airplanes. In 1971, after an economically disastrous year, three airlines were permitted to meet together and plan overall schedule reductions between several cities. The reductions increased the load factors from an average of 39 to 54 percent. Savings of $85 million and 120 million gallons of fuel were reported for the year's operation. If the Civil Aeronautics Board's goal of an industry-wide goal of 55 percent load factors is attained, 800 million gallons of fuel would be saved.

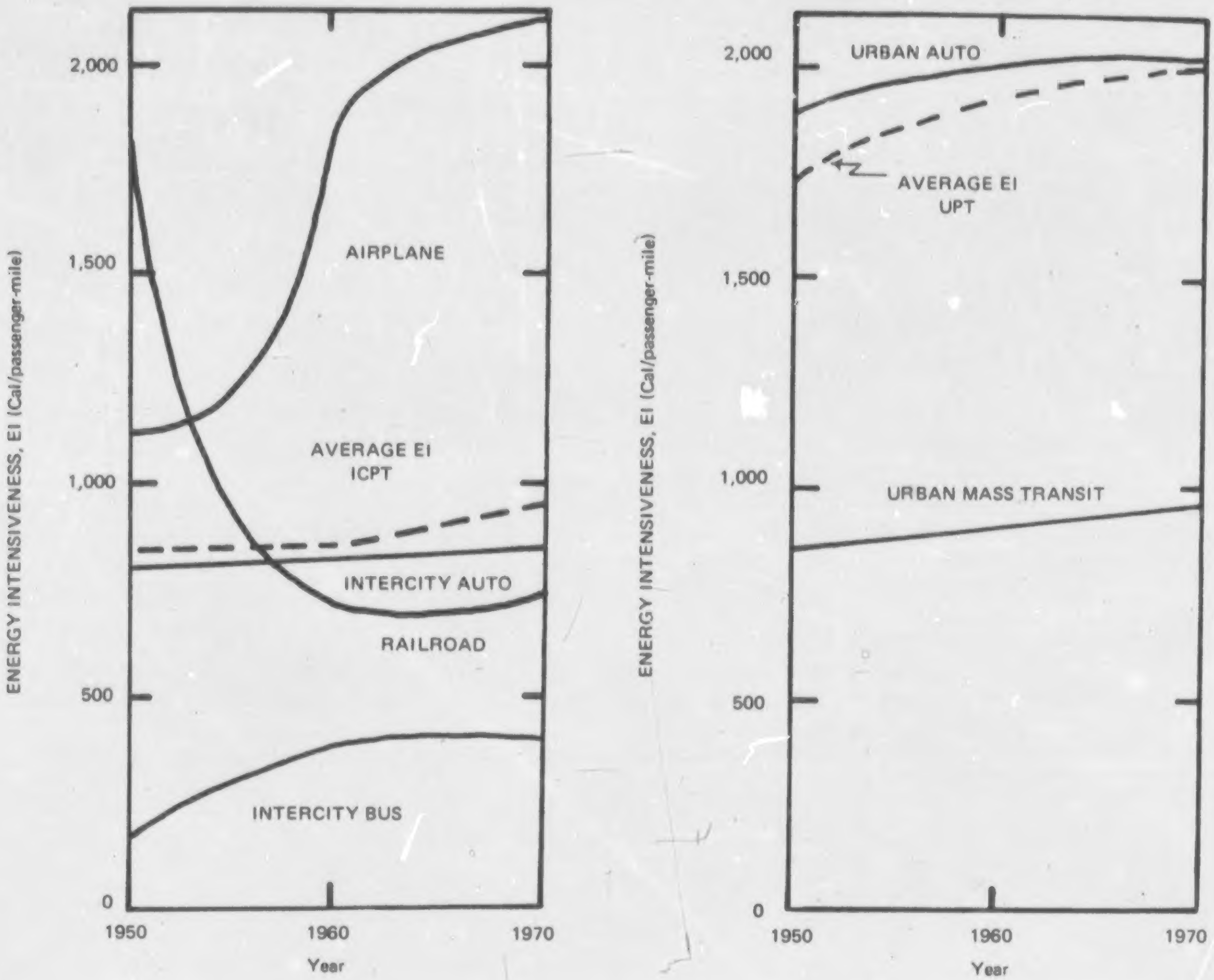
In Table 6-2 we show the savings of a variety of load factor changes, and the energy these changes would have saved at 1970 levels of operation. The biggest

FIGURE 6-5
Transportation Energy Efficiency



Adapted from: "System Energy and Future Transportation," Richard A. Rice, **Technology Review**, January 1972.

FIGURE 6-6
Energy Intensiveness of Passenger Transport



Source: "Energy Consumption for Transportation in the U.S.," Eric Hirst, Oak Ridge National Laboratory, ORNL-NSF-EP-15.

ICPT: intercity passenger transport, UPT: urban passenger transport.

TABLE 6-1
Energy Savings from Shift of Passenger Traffic from High to Low EI Mode

Transport Mode Shift*	Savings per Billion Passenger Miles	Total Savings at 1970 Level	Percent of 1970 U.S. Total Energy[a]
20% UPT, Auto - Bus	1.1×10^{12} Cal.	$.15 \times 10^{15}$ Cal.	0.9
5% UPT, Auto - Bycycle, Walking	2.05×10^{12} Cal.	$.07 \times 10^{15}$ Cal.	0.4
20% ICPT, Auto - Bus	$.45 \times 10^{12}$ Cal.	$.09 \times 10^{15}$ Cal.	0.5
20% ICPT, Auto - Train	$.15 \times 10^{12}$ Cal.	$.03 \times 10^{15}$ Cal.	0.2
20% ICPT, Air - Train	1.4×10^{12} Cal.	$.03 \times 10^{15}$ Cal.	0.2

*UPT: urban passenger transport, ICPT: intercity passenger transport.

(a) Taken as 17×10^{15} Calories.

savings, of course, come from changes in the automobile travel pattern. Car pooling has been difficult to implement, so far, but during the World War II gas rationing the average number of passengers per automobile increased from 2 to 2.7. Also, the embargo emergency did cause an increase of a few percent in urban bus loads.

Improving engine efficiency: The most straightforward way to save energy in transportation is to improve engine efficiency. We have all become aware of the range in efficiency as measured by miles-per-gallon performance. A selection of the EPA (Environmental Protection Agency) mileage test results is shown in Table 6-3.

The FEA, in its massive energy study "Project Independence," examined the gains to be expected if improvement of average gasoline mileage from 13.5 MPG (miles per gallon), which was typical of 1972 cars, were

TABLE 6-2

Energy Savings from Load Factor Increases in Passenger Travel

Transport Mode*	Load Factor Change	Savings per Billion Passenger Miles	Total Savings at 1970 Levels	Percent of 1970 U.S. Total Energy[(b)]
UPT Automobile	28[(a)]–38	$.65 \times 10^{12}$ Cal.	$.36 \times 10^{15}$ Cal.	2.2
UPT Automobile	28–50	$.90 \times 10^{12}$ Cal.	$.62 \times 10^{15}$ Cal.	3.7
UPT Bus	20[(a)]–30	$.32 \times 10^{12}$ Cal.	$.07 \times 10^{15}$ Cal.	0.4
UPT Bus	20–50	$.57 \times 10^{12}$ Cal.	$.12 \times 10^{15}$ Cal.	0.7
ICPT Airplane	40[(a)]–50	$.42 \times 10^{12}$ Cal.	$.05 \times 10^{15}$ Cal.	0.3
ICPT Airplane	40–60	$.70 \times 10^{12}$ Cal.	$.08 \times 10^{15}$ Cal.	0.5

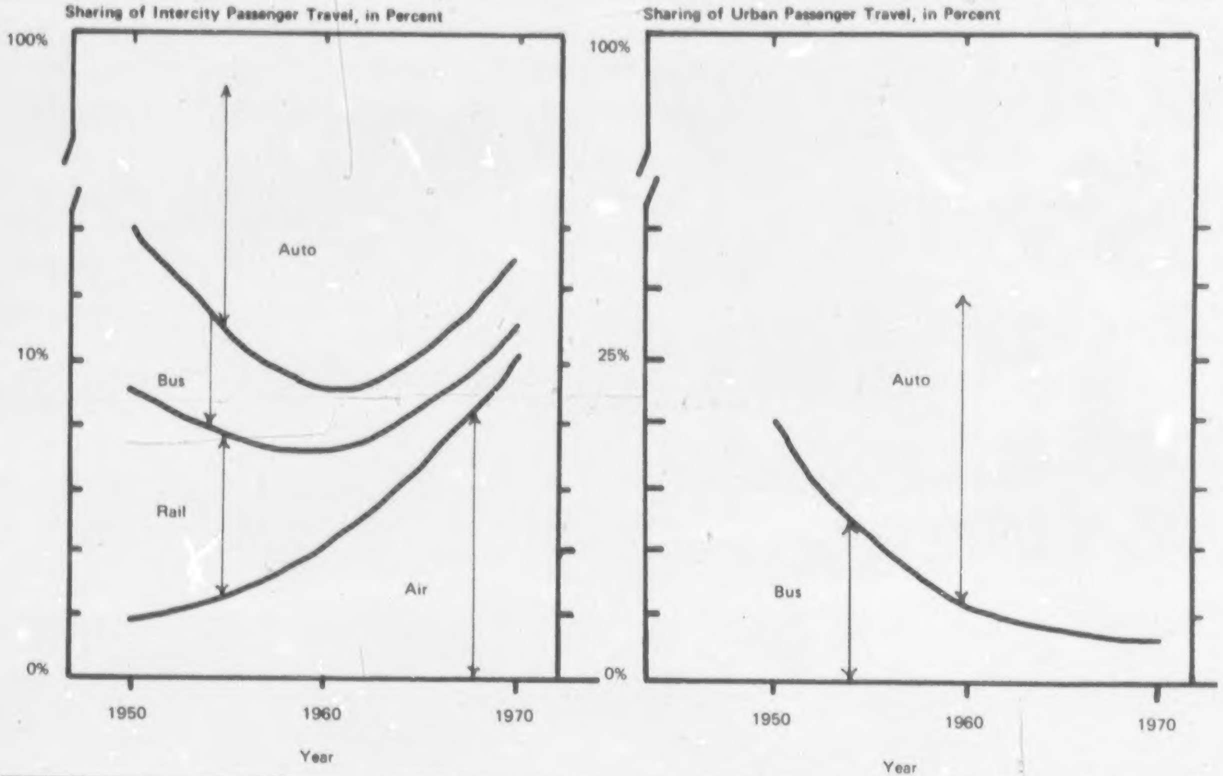
*UPT: urban passenger transport, ICPT: intercity passenger transport.

[(a)] These are approximate present levels, 28 means 28 percent full (1.4 passengers in a 5-passenger auto).

[(b)] Taken as 17×10^{15} Calories.

FIGURE 6-7

Composition of Passenger Transport



Source: "Energy Consumption for Transportation in the U.S.," Eric Hirst, Oak Ridge National Laboratory, ORNL-NSF-EP-15.

increased (by mandatory legislation, for instance) to 20 MPG in 1980. They estimate that such a measure would save 0.25 Q Calories in 1980 (if oil prices are about $7 per barrel) and 0.67 Q Calories in 1985. These savings are respectively 1 and 2 percent of the total energy consumption projected for those years (Figure 4-18, Volume II).

There is, of course, always the hope that Detroit will see the light (or perhaps "see the darkness" is more fitting) and come out with energy-efficient cars without a legislative push. The record of increasing car weights does not support this hope. The enormous investment necessary to make design changes assures that change will be slow in coming.

Moving things: In Figure 3-4, Volume II we show the growth in the energy consumed in freight transport. There is also wide variety in transport modes and in the EIs of that transport mix. We show the EIs of the most important modes in Figure 6-8. The advantage of water freight transport over land is apparent, and we see again that we buy speed and door-to-door delivery at the expense of energy. The historical record of the percentage of ICFT carried by each mode (we do not have data on UFT), Figure 6-9, shows the increasing importance

TABLE 6-3

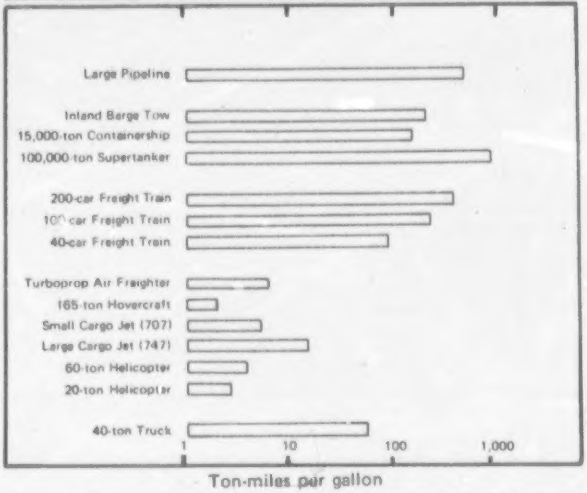
1974 Gas Mileage from EPA Suburban/Urban Test Cycle

Model	Manufacturer	Weight Class	MPG
Civic	Honda	2,000	29.1
Corolla-1 sedan	Toyota	2,000	24.8
Datsun B210	Nissau	2,250	24.9
Super Beetle	V.W.	2,250	20.9
Fiat 128-sedan	Fiat	2,250	17.4
V.W. Stationwagon	V.W.	2,500	23.7
Opel 1900	Opel	2,500	18.2
Vega Hatchback	Chevrolet	2,750	24.6
Dodge Coltwagon	Mitsobishi	2,750	22.8
Pinto	Ford	2,750	22.8
Mazda RX3 Wagon	Toyo Kogyo	2,750	10.8
Mustang	Ford	3,000	20.1
Datsun 2607	Nissau	3,000	16.1
Volvo 144	Volvo	3,000	16.1
Gremlin	American Motors	3,000	15.9
Maverick	Ford	3,000	15.0
Plymouth Compact	Chrysler-Plymouth	3,500	16.7
Nova Htachback	Chevrolet	3,500	15.2
Javelin	American Motors	3,500	13.2
Torino	Ford	4,000	14.0
Pontiac Ventura	GM-Pontiac	4,000	9.9
GTO	GM-Pontiac	4,000	8.9
Matador	American Motors	4,500	10.0
Cutlass S	GM-Oldsmobile	4,500	9.5
Plymouth Intermed.	Chrysler-Plymouth	4,500	9.2
Cougar	Ford	4,500	9.5
Ford	Ford	5,000	10.7
Lesabre	GM-Buick	5,000	10.4
Plymouth	Chrysler-Plymouth	5,000	10.4
Silver Shadow	Rolls Royce	5,000	9.3
Chrysler	Chrysler-Plymouth	5,000	9.1
Bonneville	GM-Pontiac	5,000	7.8
Eldorado	Cadillac	5,500	10.4
Buick Estate Wagon	GM-Buick	5,500	9.6
Ford Station Wagon	Ford	5,500	9.5
Chrysler Wagon	Chrysler-Plymouth	5,500	8.9
Lincoln	Ford	5,500	7.9
Toronado	GM-Oldsmobile	5,500	6.8

Source: "1974 Gas Mileage Guide for Car Buyers," U.S. Environmental Protection Agency, February 1974.

FIGURE 6-8

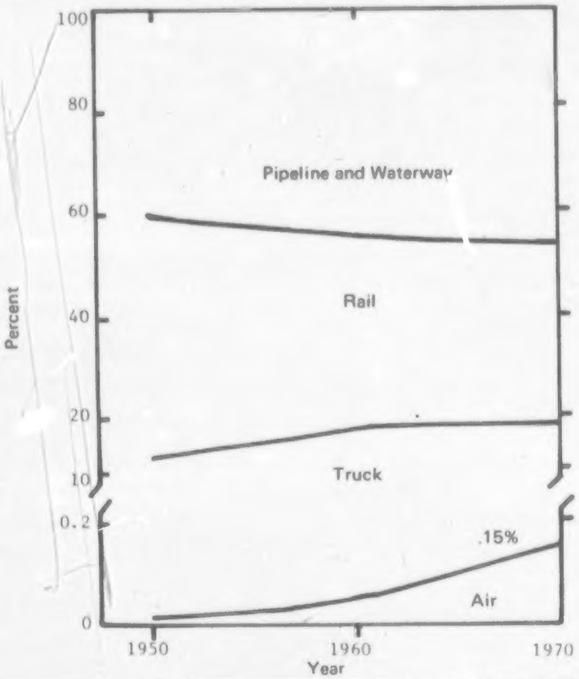
Efficiency of Cargo Transport



Source: "Energy Consumption for Transportation in the U.S.," Eric Hirst, Oak Ridge National Laboratory, ORNL-NSF-EP-15.

FIGURE 6-9

Composition of Intercity Freight Transport



Source: "Energy Consumption for Transportation in the U.S.," Eric Hirst, Oak Ridge National Laboratory, ORNL-NSF-EP-15.

of the inefficient (low EI) modes, in particular the growth of air freight.

In looking for conservation strategies in freight transport we find even more inflexibility than we did in passenger transport. Some loads can't be shifted (you can't ship automobiles by pipeline nor would you want to ship oil by airplane). It has proved difficult even to get truckers to reduce speeds. The changes that are most practical are to shift some truck freight to train and some air freight (the lowest EI mode) to truck or train.

A summary of savings which could have been obtained at 1972 levels of energy consumption is shown in Table 6-4. Only the savings in the truck-to-train shift are big enough to be significant. Air freight, however, is growing rapidly, and the same shift in 1980 would save (at the estimated rate of growth) 10 times the amount shown in Table 6-4, or 0.10 Q Calories.

Lowering the Home Fires

In the residential-commercial area there are also targets for energy conservation, even though the overall efficiency of this sector is fairly large (we compute 73 percent from the data of Figure 6-3). This combined sector consumed about 6 Q Calories of energy in 1972, 32 percent of the total. Most of this energy, 70 percent, was used in residential buildings, the rest in commercial ones. We provide in Chapter 3, Volume II, the details of the distribution of this energy among various end-uses. This can be summarized as follows:

57 percent for space heating and air-conditioning
33 percent for equipment and appliances (including cooking, water heating, and office appliances)
10 percent for lighting

This breakdown gives us our targets and even suggests strategies: reduce heating and cooling, make more efficient appliances, and lower lighting levels. We will look at the range of energy-conserving actions that can be taken in each of these areas.

Heating and cooling: There are several different but parallel approaches that can be taken to save some of the energy used to heat buildings in winter and cool them in summer. The change in the thermostat setting has been discussed. A second approach is to improve the insulation and sealing of the house to prevent the escape of heat (or its entry in summer) through roofs, windows, and cracks. There is also energy to be saved by changing the type of heating device, from electric resistance heating to gas or to a heat pump, for instance.

Thermostat lowering is the least expensive change and saves not only energy, but money. There are several other rather simple and inexpensive things the homeowner (or the commercial landlord) can do to decrease energy consumption; these are listed in Table 6-5. Also shown are the expected energy savings if those actions were to be taken by all homeowners in 1977.

Countrywide compliance would save 0.37 Q Calories. The FEA projects that heat energy, on the average, will cost \$9 per million Calories in 1977 (with \$7 per barrel oil). Thus, there would be expected \$3.33 billion saved by lowered heating bills from that action alone. If 70 percent of this savings is in the residential area and is spread among the 73 million homes (1977 estimate), the savings would be about \$320 per home. From the simple thermostat change enough money should be saved to pay for the minor tune-ups, etc., which are also suggested in Table 6-5. These in turn will save more energy and money.

Improving insulation: Similar large savings in energy can be obtained by reducing the percentage of energy used to heat and cool the outdoors. Some idea of the size of this "heat leak" is given by the following statistics:[2] An average home (one of 1,600 square feet of floor space and located in an "average" climate, such as St. Louis), if completely uninsulated, uses 1,600 gallons of fuel oil per year for heating. Full insulation, 6 inches of insulation in the ceiling and 3½ inches in the walls, reduces the consumption to 900 gallons a year, a 45 percent saving.

The attic is a prime target; it is usually accessible and about half the heat is lost there. A reasonably handy homeowner can insulate it himself at a cost of around \$150 and fuel savings will return the cost plus interest in under five years.

Another large heat loss in homes and other buildings is by air cracks around doors and windows. Storm doors

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[2] Taken from testimony in "Energy Conservation," Hearings before the Subcommittee on Consumer Economics of the Joint Economic Committee of the U.S. Congress, November 19, 1973 (pp. 54-79).

TABLE 6-4
Energy Savings from Shift of Freight Traffic from High to Low EI Mode

Transport Mode* Shift	Savings per Billion Ton-miles	Total Savings at 1970 Level	Percent of 1970 U.S. Total Energy[a]
20% ICF, Truck - Train	$.5 \times 10^{12}$ Cal.	$.21 \times 10^{15}$ Cal.	1.3
20% ICF, Air - Truck	9.6×10^{12} Cal.	$.01 \times 10^{15}$ Cal.	–
20% ICF, Air - Train	10.1×10^{12} Cal.	$.01 \times 10^{15}$ Cal.	–

*ICF: intercity freight transport.

[a] 17×10^{15} Calories.

and caulking can thus give significant returns. The potential savings (in 1977) of these kinds of investments in present houses are shown in Table 6-6. The total cost per home in the FEA Project Independence estimate is $600. The savings in the one year, 1977 (based on the estimated 73 million homes and $9 per M Calorie), amounts to $370 per home, more than half the cost.

The inefficiency of electric resistance heating: A conversion which would be more difficult to undertake, but which would conserve a considerable amount of primary energy, would be to replace electric resistance heating by gas (or oil) heat. Electric resistance heating is 100 percent efficient at the point of use, but as we see in Table 3-17, Volume II, its "system efficiency" is only 25 percent compared to 53 percent for oil and 70 percent for gas.

We can realistically only expect to make a difference in new homes. The number of new homes to be heated electrically is expected to grow from about 4 million in 1970 to 10 million in 1980 (see Figure 3-3, Volume II). The average home heating unit used 14,000 kilowatt-hours in 1970. With conversion losses and transmission losses included, each kilowatt-hour requires about 2,500 Calories for its generation. The 6 million electric heaters added between 1970 and 1980 are, therefore, projected to use 84 billion kilowatt-hours of electricity and 210 T Calories of primary energy in 1980. If replaced by 70 percent efficient gas heaters, the energy equivalent of the 84 B kilowatt-hours could be obtained from 100 T Calories of primary energy. In just the one year, 1980, a total savings of 110 T Calories could be attained. This would amount to about 5 percent of the projected total energy used for residential heating in that year.

At first glance it may not seem reasonable to replace electric energy with gas or oil, both of which are in short supply. Gas and oil, however, are both used to produce electricity. What is being examined here is the system efficiency of converting their energy to heat, then to electricity, and then back to heat again. We have, of course, oversimplified the problem: electricity comes from a variety of sources, and it is not possible to guarantee that gas-heated homes will replace gas-generated electricity. The calculation, however, does project a large enough savings to make the reduction of electric resistance heating worthy of consideration.

There is an interesting alternative form of heating which could use electricity more efficiently — the heat pump — which we describe in Chapter 3, Volume II. A heat pump, on the average, delivers 2 units of heat energy for each 1 unit of electrical energy input. Since 3 units of fuel energy are required at the power plant for each 1 unit of electrical energy produced, the overall efficiency of the heat pump of two-thirds, or 67 percent, is about the same as for a home gas heater. The FEA estimates that new homes which install heat pumps instead of electric resistance heating could save 35 percent of their annual heating bill.

Heat pumps have had maintenance troubles, and they are more expensive than resistance systems. They have the added advantage, however, of providing air conditioning in the summer; another of their positive features that should lead to growth in this form of heating and cooling.

Lighting: About 1 Q Calorie of total energy is used in lighting, 20 percent of all the electrical energy. There is considerable evidence that much of this lighting energy is wasted, that too much light is used in many commercial areas in particular. Lighting standards have steadily increased in the past two decades. Recommended classroom levels have risen from 20 footcandles[*] in 1952 to 60 in 1971; library lighting from 20 in 1952 to 70 in 1971. Commercial lighting has similarly risen and, in addition, the theory of "no-contrast lighting" has often caused these levels to be applied to non-working space.

The Federal Government has shown the way in this area by applying what is referred to as the "50-30-10 standard" (50 footcandles at work stations, 30 footcandles in work areas, and 10 footcandles in corridors and hallways). Application of these standards to Federal buildings in 1973 reduced consumption 20 to 40 percent. If such a standard were applied to the country as a whole, 0.33 Q Calories per year could be saved in 1980, according to the FEA Project Independence estimate.

Reduced lighting has a double conservation benefit in commercial buildings. Not only is energy saved directly,

TABLE 6-5
Potential Energy Savings From Low-cost Measures
Primary Energy Saved (in Q [10^{15}] Calories)

	1977
Thermostat Setback Heating (68 day/60 night)	.37
Water Heating (120)	.15
Air-conditioner (78)	.03
Reduce Hot Water Use by 1/3	.12
Furnace Tune-up	.15
Air-conditioning Tune-up	.23
Total	1.05

Source: "Project Independence Report," Federal Energy Administration, November 1974, Table AIII-12.

TABLE 6-6
Potential Energy Savings From Homeowner Investment (in Q [10^{15}] Calories)

Type of Investment	1977
Insulate Ceilings of Existing Buildings	.18
Weatherstrip and Caulk Existing Homes	.08
Install Storm Windows and Doors on Existing Homes	.03
Total	.30

Source: "Project Independence Report," Federal Energy Administration, November 1974, Table AIII-13.

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[*] A footcandle is the traditional measure of light intensity.

but an additional 10 percent or so is saved by reducing the load on the air conditioners. Many buildings need air conditioning just to remove the heat energy released in their overlit space.

Appliance inefficiency: There is a host of targets for energy savings among the appliances. These range in importance from large to small, but among them they account for about 8 percent of United States energy consumption. We show, in Table 6-7, the estimated total energy consumed by each of the major types of appliances.

Water heating is the largest category, and typical system efficiencies in this sector are low (see Table 3-17, Volume II). The Project Independence estimate is that the efficiency of a 40-gallon water heater (costing $120) could be improved considerably by an additional $15 expense (bringing electric heaters to 26 percent and gas heaters to 67 percent efficiency). This investment would be expected to pay for itself in a year. Overall energy savings would be 0.02 Q Calories in 1977.

TABLE 6-7

Appliance Energy Consumption, 1970 (in Q [10^{15}] Calories Per Year)

Residential		Energy
Water Heaters		0.44[1]
Gas	0.26	
Electric	0.18	
Refrigerators		0.19
Ranges		0.17
Gas	0.09	
Electric	0.08	
Television		0.11
Room Air-conditioners		0.09
Clothes Dryers		0.06
Gas	0.02	
Electric	0.04	
Freezers		0.06
Other		0.03
Total Residential		**1.15**
Commercial		
Refrigeration		0.09
Hot Water		0.03
Miscellaneous		0.12
Total Commercial		**0.24**
Total Appliances		**1.37**

Source: "Project Independence Report," Federal Energy Administration, November 1974, Table AIII-16.

[1] clothes washers 10%, dishwashers 5%, sinks, bathing etc. 85%

There are similar small savings to be gained from improvements in other appliances. Freezers could be better insulated. Frost-free models use 1½ times as much energy as standard models. The replacement of the pilot light with electric ignition devices has been suggested and improvement in oven insulation could save energy used in cooking. Pilot lights use 15-30 percent of the gas used in gas cooking ranges.[*]

Room air conditioners are also a prime target. Their efficiency, from the least to the most efficient model, varies by almost a factor of 3. The least efficient machine uses 2.6 times as much electricity as the most efficient to provide the same amount of cooling. Considerable improvement can be made for a 10 to 20 percent increase in the cost, with resulting large savings over the life of the device. As an example, if a 12,000 BTU room air conditioner selling for $250 is made twice as efficient, its initial cost would be about $290. The savings in operating cost (electricity) are estimated at $23 per year.

A summary of the energy that can be saved in the appliance area by modifications such as these is provided by Table 6-8. The total of 0.27 Q Calories is about 1 percent of the projected 1977 total consumption in the residential-commercial category.

Savings in the Industrial Sector

The industrial sector consumed 5.9 Q Calories in 1972 at an efficiency of 55 percent. Thus, the amount of energy and the low efficiency recommend that we focus some attention in this sector.

In Tables 3-11 and 3-12 of Volume II, we display the breakdown of this energy use by fuel, and also show its distribution among the six most energy-intensive industries. The primary metals industries are the big users, followed by chemicals (and allied products) and petroleum.

There are some general prescriptions that can be applied to all industry. In addition to the ones that were

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[*] Not all of this is wasted. If the house is being heated, the pilot light contributes usefully.

TABLE 6-8

Energy Savings from Increased Efficiency (in Q [10^{15}] Calories)

Appliances and Equipment	1977
Increase Room Air-conditioner Efficiencies	.01
Increase Refrigerator/Freezer Efficiencies	.04
Retrofit Electric Ignition for Furnace Pilots	.10
Electric Ignition in New Furnaces and	.01
Better Insulated New Water Heaters (4-7")	.02
Improve Efficiency of Other Appliances	.04
Total	**0.22**

Source: "Project Independence Report," Federal Energy Administration, November 1974, Table AIII-17.

described in the previous section — thermostat setback, insulation, turning off heat in unoccupied space, and reducing ventilation — the others that have been recommended are: burning of combustible waste (drain oil, sawdust, etc.) for heat, recirculating furnace waste heat for preheating, improving furnace controls, etc. To conserve electrical energy it is recommended that lighting levels be reduced (we described the 50-30-10 standard earlier), that loads be shifted toward off-peak hours, by starting air-conditioning or heating early in the morning and shutting it off before closing, or by shifting working hours themselves.

In addition to these general ones, there are some specific conservation targets. New production technology in the steel industry offers hope of energy efficiency which may reduce the overall energy required for steel production by 20 percent in 1985. There is energy to be saved in the petroleum refining operations, chiefly through better equipment maintenance and through recycling waste heat. Again, the FEA estimate is 20 percent reduction per processed unit by 1985.

In the plastics industry energy is an unusually important input. It takes a large amount of energy to make the products (see Table 3-13, Volume II), and the raw materials are generally petrochemicals derived from oil or gas. For these reasons, this industry is much more sensitive to the cost of energy than are others. The sharply rising costs are creating strong incentive, not only to develop new processes, but also to reduce production of the most energy-intensive plastics, and to shift from petrochemicals to feedstock materials made from coal. The FEA estimates consumption in this group of industries can be reduced 25 percent by 1985.

The food processing industry uses 5.6 percent of the nation's total energy. The major savings achievable there are through better heat management, the use of heat pumps to generate heat from waste hot water, for instance, and the burning of waste to generate heat. The FEA sees a 35 percent saving by 1985 as realistic.

In the paper products industry there are counter trends. The need for better pollution control is increasing energy use as is the increasing demand for bleached products and the decreasing use of recycled newsprint. These have been balanced somewhat by the development of more efficient processes. If recycled newsprint were used instead of virgin material, up to 30 percent of the energy consumed could be saved. The FEA estimate is for a 35 percent reduction by 1985

There are also savings possible in the cement industry, which uses a large amount of fossil fuel energy in its drying kilns. There are several techniques which could save energy in this process: heat recovery systems, more insulation on the kilns, etc. Energy savings of 35 percent are projected.

Aluminum is a particularly energy-intensive product, 18.8 M Calories per ton compared with 6.5 M Calories per ton for steel. Since most of this energy is electric, the actual consumption of primary energy is almost three times as large — 42 M Calories per ton. We are currently importing energy in this area since we import both the raw material, bauxite, and raw aluminum that has been processed elsewhere. This practice will probably continue. New refining and processing procedures under development may bring about a 25 percent overall reduction by 1985.

The food cycle, from farm to table, uses 12 percent of the nation's total energy. (It provides, however, only about 4 percent of the total as food energy.) The farm operator accounts for about half the total.[*] The major direct energy uses in agriculture are fuels for equipment and fertilizer.

Farm equipment is going diesel in order to take advantage of the higher efficiency of diesel engines; they use 27 percent less fuel for the same amount of work. By 1980 the percentage of diesel tractors is expected to have risen to 57 percent and by 1985 to 75 percent from 40 percent in 1974.

There are other energy-saving practices available. Plowing is being reduced, multipurpose equipment is being used to reduce the number of trips over the fields, and the use of natural fertilizers (compost and animal wastes) has energy advantages. There is even a return on some farms to windmills for water pumping. All-in-all, a saving of 20 percent is hoped for in this sector.

Recycling and waste recovery: Important strategies for industrial energy conservation are the use of waste materials as fuels and the replacement of virgin materials by recycled materials.

We discuss the potential for generating energy from waste in Chapter 7, Volume II. The utilization of the techniques described there could have produced about 0.21 Q Calories of energy in 1971 (this assumes burning only municipal waste in the large metropolitan areas).

Certain of these wastes are even more valuable if recycled. Recycling a ton of aluminum, for instance, saves eight-ninths of the total energy, a saving of 37 M Calories per ton. Recycling iron saves 3 M Calories per ton. Recycling paper is also energetically useful, as we have said, although this energy gain is somewhat offset by the loss of energy which could have been obtained by burning it. (The environmental analysis obviously favors recycling.)

A much publicized form of recycling is the use of returnable containers instead of "throw aways." The size of the savings realizable here is given by the calculation that 0.06 Q Calories of energy could have been saved in 1972 if *all* beverage containers had been refillable and had been refilled at least 10 times.

In most of the previous sectors we have provided estimates of the total energy savings believed possible by 1985. They total to about 4 Q Calories, about 12 percent of the projected 1985 consumption in the industrial sector. Table 6-9 gives the realistic expectations of

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[*] Here we are limiting the discussion to direct energy while in Chapter 5 our discussion of energy use in the food system included indirect energy.

Federally stimulated conservation strategies in this sector. The Federally assisted program (the FEA "Conventional Option," Project Independence Report) achieves 10 percent of these potential savings, or 0.4 Q Calories, in 1985.

Electric Utilities

Many of the conservation strategies we have just described save electric energy. There is a bonus in this conservation. Each time electrical demand is reduced by one kilowatt-hour, three kilowatt-hours worth of primary energy is left unburned at the power plant.

In addition to the frontal attack on electric energy consumption, we could save primary fuels by smoothing out the peaks and valleys in the demand. (We show a sample of the fluctuating weekly load in Figure 6-4, Volume II.) The fluctuations in the demand for electricity, which occur on an hourly, daily, weekly, and even seasonal basis, are rather large. Average demand is only about 60 percent of peak demand. To provide for that peak demand a variety of generally less-efficient generating systems is used (see Chapter 6, Volume II, for details). Any change that would lower these peaks and thus allow more reliance on the more efficient base-load generators (the large fossil-fuel and nuclear-powered plants) could save significant amounts of energy. A 10 percent reduction in peak load would save 0.065 Q Calories at 1985 energy levels.

There are several parallel approaches that could help smooth out demand. The customer's aid could be enlisted by developing a rate structure keyed to load; off-peak power would be sold for less. This approach would call for the development of meters which would store more complicated information and perhaps also contain a simple signal mechanism that would tell the user the demand level and, thus, the price of the electricity at any given time ("Don't use your dryer when the meter light is red").

The utilities themselves can cooperate to reduce peaking by interconnecting systems with different demand characteristics. Boston Edison, for instance, has a summer peaking problem, while Green Mountain Power, in Burlington, Vermont, 200 miles away, has a sharp winter peak. Regional power pools to meet these problems are becoming more and more routine.

The third leg of the approach we have already described; peaks could be flattened if peak energy could be stored and then used during valleys. We discuss some of the existing and potential systems for storing electrical energy in Chapter 6, Volume II.

The potential for conservation; a summary: In the massive Project Independence Report the FEA has put forward several of the conservation strategies we describe in the previous sections. Their analysis of the results of these programs is indicated in Figure 6-10. We also show the projected total consumption in those years and the percentage of the total projected consumption which these savings represent. Current growth rates of energy consumption are 3 to 4 percent per year. These savings are appreciable when compared to the expected growth.

The data pictured in Figure 6-10 are displayed in Table 6-10 along with brief descriptions of the type of government and private actions necessary to achieve such savings. We will finish this chapter with a discussion of these and the other mechanisms — economic and political — which may be necessary to bring about the energy-conserving practices whose results we have been estimating.

TABLE 6-9

Possible Energy Savings in the Industrial Sector (in Q [10^{15}] Calories)

Strategy	Q Calories (1980)	Saved (1985)
Industrial Investment in Energy Conserving Technology (with Federal research, development, and demonstration)	0.125	0.275
Solid Waste Recovery Systems (technical assistance from government)	0.040	0.095
Reusable Containers and Packages (stepped-up information to states)	0.005	0.010
Total	**0.070**	**0.380**

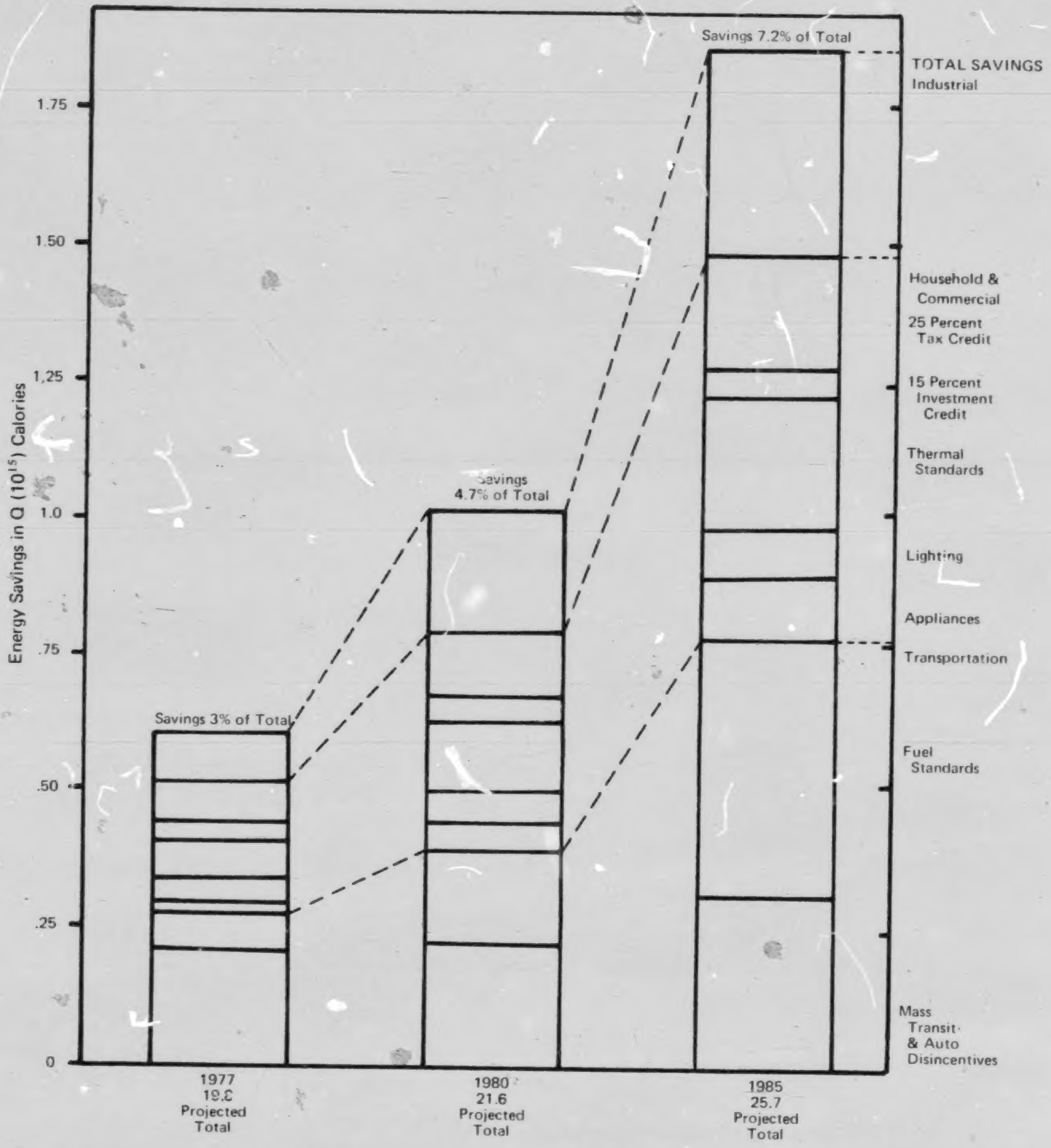
Source: "Project Independence Report," Federal Energy Administration, November 1974, Table AIII-21.

The Means of Conservation

We have spent our words, so far in this chapter, in a description of the various energy-conserving modifications which may be needed in our system. They are of all types. Some are essentially nondisruptive — lowering thermostat settings and speed limits are essentially of this type — while the switch from the convenient personal transportation of the automobile to less energy-intensive mass transportation might cause some disruption of lifestyle. Some of the modifications could be accomplished at no initial cost; they, in fact, save money while others require an initial investment, at least, before any savings occur. They all have one feature in common. None will occur spontaneously. A variety of mechanisms will need to be set in place in the complex workings of our society to bring them about.

What are the mechanisms that can cause individuals and corporations to adopt one or the other of the strategies we have just described? There are several, but the bulk fall into one of the following categories: marketplace pressures, government assistance and incentive, and government regulation. The final mix of these mechanisms this country chooses will form the skeleton of that rare beast, an "Energy Policy." The design of that beast is now under way in hundreds of government offices and corporate board rooms. If we are to contribute as informed citizens to that design, we

FIGURE 6-19
Savings from Conservative Policy Options for $11 Oil



Source: "Project Independence Report," Federal Energy Administration, November 1974, Figure III-2.

need to have some insight into the variety and effectiveness of mechanisms available to us.

The Pressures of the Marketplace

It is a canon of a free enterprise society that decisions should be made in the marketplace. Only through the myriad of signals that come from the interplay of supply and demand can we achieve a stable system. The price system — so this canon goes — should do a better job of planning than any "planning committee." Only in the marketplace can it be decided how much oil is needed, for instance, by determining what the consumer will pay for it; only in the marketplace can the question of how much oil should be produced be answered, by finding out what it costs to produce it. The "marketplace" answer to an energy shortage is "raise the price."

TABLE 6-10
Conservation Actions and Savings At $11 Per Barrel Oil, 1980 and 1985 (in Q [10^{15}] Calories)

Conservation Actions	1977	$11 Oil 1960	1985
Transportation			
Establish a mandatory 20 mpg auto efficiency standard	.07	.17	.47
Enact legislation and establish programs that would substantially increase the use of public transit and discourage the inefficient use of automobiles, such as a gasoline conservation fee	.21	.22	.31
Total Transportation Sector[1]	**.28**	**.39**	**.78**
Residential and Commercial[2]			
Subsidy such as a 25% tax credit for retrofit of existing homes, expiring in 1980	.07	.12	.21
Subsidy such as a 15% investment credit for energy reduction investments in existing commercial buildings, expiring in 1980	.04	.04	.05
National thermal efficiency standards for new residential & commercial buildings	.07	.13	.24
Mandatory lighting standards for commercial buildings	.05	.06	.08
Appliance efficiency standards	.01	.05	.12
Total Residential and Commercial Sector	**.24**	**.40**	**.70**
Industrial			
Aggressive conservation programs assisted R&D for increased efficiency in industrial processes	.09	.23	.38
Total Net Savings[1]	**.60**	**1.01**	**1.85**
Utilities[3]			
Demonstrations in support of adding energy conservation standards to the Federal Power Act	.02	.12	.23

Source: "Project Independence Report," Federal Energy Administration, November 1974. Table III-5.

[1] Savings not entirely additive since auto disincentives would induce some increased new car efficiency.

[2] The gross savings wold be higher since losses due to generation and distribution of electricity would be included.

[3] Savings in electrical generation result from decreasing the fossil fuel input required to generate the electricity demand in the three end-user sectors.

It seems clear from our recent experience, as well as from sophisticated analysis of economic models, that the soaring price of energy will bring some semblance of balance, and that the projections of energy consumption made in the late 1960s (see Chapter 4, Volume II) already overestimate energy growth. The FEA analysis in the Project Independence Report projects annual growth rates of 2.7 and 3.2 percent (depending on the price of oil) instead of the average of 3.5 percent of Figure 4-18 (Volume II). (As we have reported, energy consumption fell by 2.2 percent in 1974.)

Unfortunately the multidimensional problem we describe in this Source Book cannot be handled on a simple supply-demand basis. There are two serious distortions of the price system which make the present energy price unrealistic. On the one hand energy is subsidized, while on the other hand there are energy costs (environmental costs, for instance) that are not reflected in the price.

Subsidies: There is a great variety of visible and hidden subsidies which conspire to make the apparent price of energy to the consumer lower than its real price. Energy for some time has been "expensive except for the price," to quote Lawrence Moss of the Sierra Club.[3]

One type of subsidy has received most notoriety in the oil business — the depletion allowance and other tax write-offs — but such allowances are working against energy conservation elsewhere.

The depletion allowance provides a tax exemption for a portion of the net income received from producing a national resource. These allowances are based on the perceived importance of the energy resource: oil, gas, and uranium have a 22 percent depletion rate (22 percent of the income is exempted); oil shale has a 15 percent rate, and coal 10 percent. They are intended to encourage and reward continued production of important natural resources.

The oil companies have several other tax advantages. They, along with other resource producers, for instance, are allowed to deduct some of the investment expenses of exploration and development. Another significant tax break for the international oil companies is their ability to write off the heavy foreign taxes on the oil they produce overseas. Many economists believe that these royalties paid to foreign governments should be classified under expenses. The present provision allows them to be deducted from the United States taxes due on income. This deprives the Treasury and the taxpayer of several billion dollars.

The net result of these various tax-related subsidies is to make the apparent price of energy lower than the cost. The difference is made up by an assessment on taxpayers; but in hiding it this way, the clarity of the price signal is lost and customers buy more energy than they should.

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[3] Testimony before the Energy Conservation Hearings of the Committee on Interior and Insular Affairs, Part I, Serial #93-7, March 1973, p. 225.

There is also a set of hidden subsidies that encourage oil consumption in transportation in particular. An example is the tax money that builds roads and airports. Gasoline cost, therefore, does not show the real cost of the trip any particular user may make and, further, these subsidies favor the truck over the less energy-expensive railroad for freight transport.

A similar distortion is at work in the electric utility industry. The utilities are what economists call a "natural monopoly." It does not make sense to have more than one utility and, therefore, more than one set of power or gas lines serving a community. The way to operate a natural monopoly is by what is called "marginal cost pricing." The price should be based on the cost of the last unit produced since this price will tell the customer what it will cost him to buy the next unit.

The electric power industry for several decades was a decreasing cost industry. (This is typical of all rapidly expanding industries.) The last unit of electricity produced (from the new efficient generator) had been cheaper than the average cost. If the price were set at this cost, the utilities would lose money. In order to avoid this and to take advantage of these decreasing costs, the public agencies which regulate the utilities allowed discriminatory pricing — different prices to different classes of users — and the so-called "declining block rates."

In this rate structure the charge to each class of customer decreases as consumption increases. In the first block electricity might cost 2.5 cents per kilowatt-hour, in the next 2 cents, and so on. Thus, demand is increased, the production system is enlarged and becomes more efficient, and average costs to all decrease.

The economic situation has changed in the past two or three years. The utilities (gas and electric) are no longer declining cost industries. All costs are now increasing and the utilities are no longer appreciably improving efficiency with new equipment or larger systems. Increased demand often calls into service older plants or less efficient peaking units. The last unit of energy produced is now the most expensive.

Many economists, therefore, are now calling for revisions in the rate structure which would reflect present realities and inhibit, rather than stimulate, growth. If pure marginal cost pricing is applied, however, the companies would get "windfall profits," for the average cost is, and will continue for some time to be, less than the cost of the last unit produced. New rate structures will have to be designed which give the proper price signals. One suggestion is for a "reverse declining block" which prices the first block low (so as to provide inexpensive energy for the poor) and raises the price to the bulk consumer (who may then pass it along on the goods he produces).

Many economists are now calling for a return to at least the principle of marginal cost pricing in all energy industries. If natural gas costs 45 cents per million cubic feet, on the average, but $1.00 for the last few million cubic feet, then the customer better not be allowed to buy gas at 45 cents for he will increase his demand. The "windfall profits" that a real marginal cost pricing would bring could, it is argued, be reduced by taxes and used for further energy research, for instance. Only with such a change can the price system bring energy supply and demand into balance.

The energy economists make a convincing case for changes in the energy price system. What these changes should be, of course, is far from clear and the advocacy and opposition to various proposals should keep us informed and entertained for some years.

There is substantial agreement, however, that a pure price system will not suffice, that government intervention will be needed if we are to establish a realistic energy policy.

An "energy policy," in fact, means intervention since it sets up goals that are different from simple supply/demand goals. The government, of course, has traditionally intervened. The subsidies we have just described were intervention. The "oil import quotas," which were in place for many years, were another form of intervention. They were designed to encourage domestic production of oil so that we would not become overdependent on foreign sources. They kept oil prices higher in this country than abroad for several years, but in the end were removed because, in fact, domestic production did not keep up with demand.

It seems clear, from our history as well as from our present state of confusion, that we must design a national energy policy. We have discussed some of the mechanisms of policy-setting in a previous chapter and will summarize some of our options in the next chapter. In the remaining paragraphs of this chapter we will briefly describe some of the methods of intervention which may be effective in bringing about the energy-conserving practices we have described.

The Carrot and the Stick

Government intervention, of course, can take many forms and have many points of application, but, generally, we can classify them under the "carrot" of tax incentives, for instance, or the "stick" of punitive taxes, regulation, etc. We will look at several of the suggested actions.

A sample of the types of measures suggested is provided by the items of Table 6-10. There are several "carrots" there. The retrofitting of older houses with insulation, storm doors and windows, etc. is to be encouraged by a tax credit for the investment. A similar tax incentive is to be provided for commercial landlords.

A different sort of carrot is suggested in the industrial sector and for utilities. There the Federal Government, it is proposed, will take the leadership in carrying out the necessary research and development for energy-conserving practices and equipment and will also support demonstrations of these developments.

There are "sticks" suggested also. The improvement in automobile gasoline mileage is to be achieved by mandatory legislation. A variety of techniques is available to increase the use of public transportation. Consumer costs could be increased by raising tolls on bridges and highways leading into cities, by increasing urban parking fees and by establishing auto-free zones in cities. Higher gasoline taxes are also a formidable stick that is being seriously considered, and behind that stands the specter of rationing.

There are also some carrots available to entice people to mass transit. It is suggested that Federal money be used to subsidize the improvements needed to make the service more attractive and effective.

The carrot of tax incentive for retrofitting existing buildings could be backed up by the stick of stricter thermal efficiency standards for all buildings. This, of course, will require massive revisions of building codes, etc. One could add to these standards mandatory and lowered lighting standards for commercial buildings.

Caveat emptor — let the buyer beware: An additional carrot to the consumer, in these times of high energy prices, is information on the efficiency and the fuel and operating costs of large and small appliances offered to him for purchase.

An effective effort in this direction will need be a cooperative one. It will have to be required by law, no doubt, but will need the cooperation of the many industrial trade associations and monitoring perhaps by the Bureau of Standards.

What is aimed for here, and in many of the actions for energy conservation, is a change in public thinking. We are presently geared to first cost. "What is the purchase cost?" We must change to life-cycle costing. "What will it cost year by year?" It is only through an appreciation of life-cycle costs that the price system, through increased energy prices, can get the energy conservation message to the pocketbook where it will make a difference.

The hidden environmental costs: Even with the changes we have just described, one of the goals of an enlightened energy policy will not be served. There are neither sticks nor carrots described whose purpose is to improve and protect environmental quality.

We must put this goal into the price system by "internalizing" (in economic jargon) the costs of environmental damage. We must make visible, in the bill for energy, the cost of reclaiming strip mines, of using land, air, and water as dumping grounds for pollutants, of protecting nuclear fuels from theft, and generally of preventing and correcting the damage and hazards we described in Chapters 2, 3, and 4.

To accomplish this we will have to call into play a variety of strategies. Pollutant emission can be taxed or regulated. Strip mine operators can be required by law to reclaim land to a certain standard (as they increasingly are). Beneficial uses of waste heat can be developed and demonstrated, development of nonpolluting energy technology can be supported and encouraged. The whole structure of taxes and regulation must be re-examined from a new point of view. Present freight rates, for example, now discriminate against recycled materials in favor of virgin materials. The depletion allowance available to pulpwood producers makes it possible for them to undersell recycled newsprint. The same depletion allowance operates against the recycling of lubricating oils.

If we are to have effective energy conservation, it will have to be on a "pay-as-you-go" basis. We must see that the system is restructured to take into account all the costs of energy. We must be certain the price is right.

Summary

A component of all likely energy policy options is the requirement to conserve energy. This may vary in its intensity from option to option and its urgency may change over time if we emphasize "dig and drill" or as new energy sources come on line. The shortages, the increasing prices, and the need for adding on environmental costs, however, will cause the price system by itself to force wiser use of energy.

In this chapter we reviewed the short-term conservation strategies and then looked at the potential for longer-term savings in the various economic sectors. The short-term strategies are largely aimed at the individual consumer. He is asked to lower his speed, drive less, and reduce the comfort level in his house and office. These requests can be backed by allocation and, if necessary, rationing.

The transportation sector is a prime target for long-term as well as short-term strategies. It uses a quarter of our energy (and that inefficiently) and the most sensitive fuel, oil. The strategies proposed are all aimed at reducing overall energy intensiveness (EI), at reducing the Calories per ton or per passenger mile. This can be accomplished by improving engine performance, by switching passenger or ton miles from high to low EI modes (from the automobile to mass transit or bikes, for instance) and by increasing load factors (the percentage of filled capacity in a mode of transport).

In the building sector (residential and commercial) long-range strategies require modification both of structure and practice. Improvement of insulation and the addition of storm doors and windows could save trillions of Calories. A switch away from electric resistance heating either to direct fuel use or to the electric heat pump would also reduce primary energy consumption. Lighting is a special target; lowering levels would not only reduce energy use directly but indirectly, in many instances, by lowering the air-conditioning load.

In the industrial sector a variety of energy-conserving changes could be brought about. Waste heat can be reused and waste materials burned for heat. New processes are being developed which are less energy intensive. Recycling offers important energy savings particularly in the production of paper, steel, and aluminum.

In the final section we examined some of the mechanisms that will be needed to implement these conservation strategies. The price system, with the present distortions of tax incentives, special rate structures, etc., and without the inclusion of environmental costs, is not working. We will have to be led toward energy conservation by a "carrot and stick" approach. Among the carrots are tax incentives to insulate existing buildings and subsidies for mass transportation systems. Among the sticks, for instance, are mandatory legislation of better gasoline economy (20 MPG by 1980), gasoline taxes, stricter thermal standards on new buildings, and taxes and laws to require environmental restoration and protection.

The FEA in its Project Independence study looked carefully at the options and the mechanisms for implementing energy-conserving strategies. They forecast a real possibility of savings, growing from 3 percent of the projected total energy in 1977 to 7 percent in 1985. Some of the changes which must be brought about are simple and non-disruptive, some will disrupt sectors of the economy and our lifestyles. We are, however, in a new era and energy is no longer free. It is time to open the savings account.

CHAPTER 7

Energy Policy and Options for the Future

Energy Policy and Options for the Future

Throughout this volume of the Source Book we have tried to evoke the image of a web interconnecting all our activities as a symbolic representation of energy's broad role. We examined several of the web's strands: those which connect energy at many points to the environment, to the production and consumption of goods and services, to employment and consumer spending, to the growing of food, and even to foreign policy.

The web analogy, however, fails us in this chapter when we begin to think of policy. The web produces an image of centralized power and decision-making, and energy policy-making in this country does not evoke that image. Rather than a single center of policy-making, which coordinates, disseminates, and implements some master plan, energy decisions in this country have been made in semi-autonomy in almost 100 different agencies and departments. There has not been a "National Energy Policy."

For a long time, of course, there seemed no urgent need for an energy policy, just as there seemed no need for a land-use policy when land was plentiful. The day of free energy is over, however, for at least the three decades or so it will take our experiments with solar energy and fusion power to prove out (see Chapter 7, Volume II). The web we have been describing is now stretched tight and if it is jangled anywhere, the disturbance spreads throughout the system. We must now put intelligent planning at the center.

The Fragmented Past

The responsibility of directing the production of energy in this country has been shared between the private and public sectors. The production of oil, coal, and uranium has been almost entirely under the aegis of private enterprise. While gas production is left to the private sector, its transmission and distribution, and therefore its price, have been regulated by government bodies. Hydroelectric and nuclear power have been developed under public and regulated private ownership. Of the other segments of the utility industry, those which are investor owned, are publicly regulated while those which are publicly owned are not regulated.

That such a crazy-quilt pattern of planning and control was able to function at all was due to the simplicity of the motto common to all the component groups: "More is better." Such a motto was an obvious choice of the energy-producing operations in the private sector. Government actions at the state and Federal levels were mostly supportive and promotional.

We presented some sampling of the confusion that this fragmentation of planning and control brought about in our brief description of "The Shootout at Four Corners" in the introduction. In the Department of the Interior alone, the Bureau of Reclamation, the Bureau of Land Management, the U.S. Geological Survey, the Bureau of Indian Affairs, and the National Park Service were all involved. At least two additional independent Federal agencies were also deeply embroiled, the Federal Power Commission and the Environmental Protection Agency. Before the ruckus had died down the U.S. Congress and the courts also played important roles. Outside of the Federal Government, of course, important decisions were being made in state houses, tribal council meetings, and corporate boardrooms.

We cannot take the space here, nor do we feel it appropriate in this Source Book, to undertake a detailed analysis and critique of the policy decisions and non-decisions which brought us to this point of over-demand and under-supply.[1] What we will do is briefly sketch the functional structure of the various government agencies with major energy-environment responsibilities, then take a look at past policy trends and future policy choices in the areas of fossil fuels and electric utilities.

Government Energy Responsibility

The energy-environment responsibilities of the Federal Government are divided among the three branches in the same manner as are all responsibilities. Congress makes the laws, the Executive Branch implements them, and the Judicial Branch judges and referees them and their application. All of these branches have played active and important roles in determining past energy policy and will play similar roles in the future.

Government responsibility can be broken down along functional lines also, and we will use such categories in this discussion.[2] The four areas of most importance are: policy development; regulation; research and development, and energy resource development. We will consider each of these briefly:

Policy development: As we have said, there has been relatively little attention paid to this area in the past; and the recent past has been confused by authority for policy-making shifting back and forth among Presidential "Energy Advisers," the Federal Energy Office, and Cabinet members.

The Federal Energy Administration (FEA), established in 1974 for a two-year term, is presently charged with policy development, data collection, and some regulatory functions. Under William Simon it was the dominant energy policy body, but its role at present is not as clear. In a later section we will discuss the "Project Independence Report" of the FEA, the most thorough policy document now in existence at the Federal level.

Other Federal agencies which play some policy role are the Office of Management and Budget, the Council on Environmental Quality, which advises the President on energy-environment matters, and the Council on Economic Advisors, for which energy matters have assumed a high priority.

There are several Congressional committees which have conducted hearings and developed legislation of a policymaking nature; reference to them will be found in the bibliographies of "The Energy-Environment Materials Guide."[3]

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[1] Several books and articles on U.S. energy policy are referenced in Section XI, Part I, of the NSTA **Energy-Environment Materials Guide**, which was produced along with this Source Book.

[2] In this section we summarize material that is presented in more detail in Appendix E of "A Time to Choose," final report of the Energy Policy Project, Ford Foundation, Cambridge, Massachusetts: Ballinger, 1974.

Regulation and control: There are several different types of regulation and control in the energy-environment area: economic regulation, fuel allocation and control, energy facility siting and land use, and environmental and safety regulation.

The major responsibility for economic regulation falls on the Federal Power Commission (FPC), which regulates the price of natural gas and has some control over electricity sold wholesale in interstate commerce. The FPC also exercises what amounts to a policy role with its Federal Power Surveys that project national needs.

Other agencies with regulatory input are the Securities and Exchange Commission, which looks at ownership and financing in the energy industry, and the Justice Department, which enforces the laws. The Interstate Commerce Commission sets freight rates and has important effects on recycling, for instance, by determining the difference between freight rates on virgin and recycled materials. At the state level there are also Utility Commissions, which set the consumer prices for electricity and natural gas.

The area of energy facility siting and land use has been a chaotic one, with most decisions — where power plants and refineries will be built, or what strip-mine reclamation is required — made at state and local levels. The FPC approves siting of hydroelectric facilities and the (now defunct) Atomic Energy Commission licensed nuclear plants. (This function will be carried out by the National Regulatory Commission, see discussion below.)

Decisions on environmental protection and safety have also been fragmented. The principal responsibility defined by various environmental protection legislation of the past few years has fallen on the Environmental Protection Agency (EPA). This agency sets guidelines for state enforcement. It is most active in air, water, and land pollution. The responsibility for assuring the safety of nuclear facilities has been with the AEC, but with its demise it now falls to the new National Regulatory Commission (NRC).

The regulation of public land use falls on the Bureau of Land Management of the Department of the Interior with the technical assistance of the U.S. Geological Survey. The enforcement of the new Mine Health and Safety Act is the responsibility of the Interior Department's Mine Enforcement Safety Administration (MESA).

Energy research and development: The responsibility for research and development has been divided. The largest amounts of money in the past two decades went to the AEC for the development of atomic power. The Bureau of Mines and the Office of Coal Research of the Department of the Interior had some money for fossil fuel R&D. The National Science Foundation and lately the National Aeronautics and Space Administration (NASA) have also supported basic research in the energy area.

In the new reorganization, the R&D responsibility will fall to the Energy Research and Development Administration (ERDA), which will absorb the AEC research and development functions and some others that have been scattered throughout the various agencies.

Energy resource management: This important responsibility, to find and assess the worth of public-owned energy resources and then to lease them and supervise their extraction, falls to the Department of the Interior. The work is performed for the most part by the Bureau of Land Management and the U.S. Geological Survey. The Bureau of Reclamation also occasionally gets into the act with its plans for developing regional programs that involve energy resources.

Energy conservation: In the past there has been little federal (or other) direction for energy-conservation efforts. But for the past year the FEA has had a conservation division which has undertaken studies and supported research in the building, transportation, and industrial areas. It is to be hoped that conservation efforts will be vigorously pushed forward by ERDA or the FEA.

The Private Sector

Rather than try to break down the private sector by companies, councils, etc., we will look at the policy-decision trends of the recent past and future for the three fuels and electricity generation.

Oil: The giants in the energy business are the oil companies. Of the 10 largest industrial corporations in the United States, 4 are oil companies; of the 15 largest multinational companies, 7 are oil companies.* The combined dollar sales of the top four United States oil companies (Exxon, Texaco, Gulf Oil, and Shell) was $57 billion in 1973, more than the total GNP of many countries. The 1972 sales of the 20 largest United States oil companies are shown in Table 7-1.

The great economic power of the oil companies is, of course, accompanied by political power. To a large extent they have been the policymaking body as far as oil production is concerned, deciding how much oil was produced, and where. Government policy and intervention in the market have been supportive. We briefly mentioned several components of government policy in the previous chapter: the subsidies provided by the "oil depletion allowance," the deduction of intangible drilling costs, and the deduction from United States income taxes of the money levied on crude oil produced on foreign soil. For many years domestic production was protected by the import quota from competition from (previously) inexpensive foreign crude oil, and by "prorationing," a system of state controls on production that matched well-by-well production to demand, and made certain that there was little surplus oil on the market. Prorationing was necessary in oil fields on which several owners were pumping from the same pool (like several straws in the same soda) for it prevented a mad rush to get all the oil out of the ground. It protected resources, but it also thwarted the marketplace pressures and supported oil prices.

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[3] op cit.

*Exxon, Standard of California, Standard of Indiana, Royal Dutch/Shell, British Petroleum, Texaco, and Gulf. With the French Compagnie Francaise des Petroles, they produce about two-thirds of the world's oil.

All of these government programs were designed to stimulate domestic production of petroleum. In spite of them, however, as we show in Chapter 5, Volume II, domestic petroleum production peaked in 1970 and has been declining since. And in spite of these favorable provisions, we have experienced a growing shortage of petroleum products and our dependence on unstable foreign supplies has increased each year. To understand how these supportive policies led nonetheless to shortages and high prices, we must look at the way in which government policy interacted with oil company policy and structure.

Structure plays a most important role. The oil industry is dominated by 18 huge companies (see Table 7-1 for top 20). These 18 companies are among the 200 largest companies in the country, 10 are in the top 40 and four in the top 10. They are "vertically integrated companies," which means they operate at each of the four basic levels of the petroleum industry — crude oil production, refining, transportation, and marketing. The four top companies, for instance, controlled 37 percent of the proven reserves in 1970 and the top eight, 64 percent. The same dominance exists at other levels. The top four own a third of the refining capacity (the top eight, 58 percent). The major companies own outright, or jointly, most of the pipelines. Not unexpectedly this dominance extends to marketing; the top four made 31 percent of the total gasoline sales in 1970 (the top eight, 55 percent).[4]

With this integrated structure, the major oil companies have significant advantages over independent producers, refiners, and marketers. Because of this structure, the previously mentioned policies, designed to protect and stimulate domestic production, have not always achieved that end. We will take a few examples from the Senate investigation of 1973 to make this point.[5]

The Oil Import Control Program restricted crude oil imports and limited imports of gasoline almost to zero. This restriction on foreign crude plus the majors' control of most domestic crude, and of the pipelines, made it very unprofitable for an independent refinery to operate. They could not be assured of the raw material. For a variety of reasons, and local opposition to refinery siting is only one of them, the majors did not build the additional refinery facilities needed during the 1960s and since independent refineries were discouraged, we entered the 1970s without sufficient refinery capacity.

The control of all phases of petroleum production and marketing enables the major companies, if they desire, to use the depletion allowance and the other tax advantages for a competitive edge over independent refiners and marketers. These tax advantages are applied to the

TABLE 7-1
The Oil Companies, Total Sales and Ranking by Assets in the Fortune 500 List, 1972

Company	500 Ranking by Assets	500 Ranking by Sales	Gross Sales (Millions of Dollars)
1. Exxon	1	2	20,310
2. Texaco	3	8	8,693
3. Gulf	6	11	6,243
4. Mobil	7	7	9,166
5. Standard of California (Chevron)	9	12	5,829
6. Standard of Indiana (Amoco)	12	15	4,503
7. Shell	14	17	4,076
8. Atlantic-Richfield	16	25	3,321
9. Phillips Petroleum (66)	25	36	2,513
10. Continental Oil Company (Conoco)	26	24	3,415
11. Sun Oil (Sunoco)	28	59	1,918
12. Union Oil Co.	30	52	2,098
13. Cities Service Company (Citgo)	35	63	1,862
14. Getty Oil Company	42	100	1,405
15. Standard of Ohio	55	95	1,447
16. Marathon Oil Company	77	113	1,278
17. Amerada Hess Corporation	90	107	1,334
18. Ashland Oil Incorporated	93	70	1,780

Source: Albert J. Fritsch and John W. Egan, **Big Oil: A Citizens Factbook on the Major Oil Companies**, Center for Science in the Public Interest, Washington, D.C., 1973.

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[4] These data on the major oil companies' structure are from "The Investigation of the Petroleum Industry," Permanent Subcommittee on Investigations of the Committee on Government Operations, U.S. Senate, July 12, 1973.

[5] Ibid.

production of crude oil. It is thus possible for the integrated companies to sell themselves crude oil at high profits (an internal transaction) and then to lower the income taxes on these profits by these special deductions. They can then operate their refining and marketing operations at cost and thus obtain an important advantage over the nonintegrated independents who have to actually buy the high-priced crude oil and make such profits as they can from refining and/or marketing. In 1973 the rise in crude oil prices and the shortage of gasoline drove many independent retailers out of business by removing the price differential which had been their major advantage.

We have described the operation of the special provisions to show that they were designed to help the oil companies and thus stimulate the production of this precious resource. They have certainly helped. The oil import quota, while it was in operation, kept our oil prices a dollar or so a barrel higher than they would have been if foreign oil had been allowed to compete. The depletion allowance is of great importance to small, independent domestic oil producers.

One could, of course, also argue that the existence of the quota kept our dependence on foreign oil at lower levels than it would have been otherwise. Unfortunately, the tax deduction allowed on the money paid to foreign governments worked in the other direction. This is made clearer with a little arithmetic. Suppose a United States oil company earns $100 million abroad and pays $60 million of this to the foreign government. The United States tax liability on the $100 million would normally be 48 percent, or $48 million dollars. If the $60 million is treated as income tax paid to a foreign government (the present interpretation), then the company owes no United States taxes because the $60-million deduction is greater than the taxes owed. If the $60 million had been treated as a business expense, then the company would have deducted it from the $100 million and paid 48 percent taxes on the remaining $40 million, about $19 million. The advantage of this tax interpretation is that the multinational companies paid income taxes in 1971, for instance, of about 7 percent on their total operation (as against the 48 percent that other corporations, including independent refiners and marketers, pay).[6] It has thus been economically much more attractive for these international companies to develop Middle-Eastern wells rather than American ones.

The oil import quota has been rescinded and the domestic "prorationing" is no longer effective since domestic wells are now operating at 100 percent of capacity. As we stated in Chapter 6, there are strong arguments to remove the other subsidies from oil production. On the face of it they do not seem to have served to increase domestic production as they were designed to do and they have resulted, overall, in concealing from the consuming public some of the costs of oil products. Their removal, and the subsequent price rise, should encourage more efficient use of this precious liquid and also encourage the development of other energy sources which have not had similar subsidy.

Gas: The government has not been quite so supportive in its handling of natural gas. Gas is produced along with oil at many locations and so enjoys the same tax benefits. It has not been imported from the Mideast and so is not helped by the write-offs we have just examined. The big difference has been in the regulation of its price by the FPC, a practice that was upheld by the U.S. Supreme Court in 1954.[7]

Regulation of gas prices was established to protect the consumer. Since in the beginning most natural gas was discovered along with oil, the companies could reap "windfall profits" if they were allowed to take the same tax breaks and sell gas at prices similar to oil. As a result of the regulation, natural gas has been an energy bargain and its use, as we show in Chapter 5, Volume II, has grown rapidly.

Natural gas is now in even shorter supply than oil, and exploration for it has also been declining. There is now great pressure to deregulate its price and promises are made that the supply will increase rapidly as the price rises. Proponents of this course of action point to the fact that more natural gas is produced now as "unassociated gas," gas found independently of oil. A larger return on investment, they argue, would encourage more exploration for gas. However, if all gas (new and old, so to speak) is deregulated, great profits will be realized on the gas already being produced. A vigorous debate is going on within the concerned agencies and within Congress over the wisdom and effectiveness of deregulation.

With the shortage of domestic gas has come increased interest in importing liquid natural gas (LNG), and a new form of government intervention. Our government is heavily subsidizing United States construction of LNG tankers and the Maritime Administration guarantees 75 percent of the ship mortgages. These are again costs borne by the taxpayer and hidden from the consumer. They tend, therefore, to encourage increased consumption of this fuel.

Coal: Coal has operated more nearly in a free market economy without the subsidies and tax advantages we have mentioned. It has a depletion allowance of only 10 percent. Coal production has not expanded very much since the 1940s (see Chapter 5, Volume II, for data). Rather than encouraging production, in fact, Federal Government policies have been a handicap in many ways.

One example of this was examined in Chapter 3 of this volume. The passage of the new Mine Health and Safety Act has had the beneficial effects we described, dramatically reducing accident rates. It also promises lower incidence of Black Lung and brings the payments for this disease out in the open, causing it to be added to the price of coal. It appears, however, that the new safety regulations have driven many small mines out of business. The strict air pollution laws have also come down hardest on coal.

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[6] "Energy, The New Era," S.D. Freeman, Vintage Books, New York, 1974.

[7] Phillips Petroleum Company v. Wisconsin, 347 U.S. 672, June 7, 1954.

In addition, the Federal Government has created a vigorous competitor for coal's major market, the electric utility industry. As we see in Chapter 6, Volume II, the Atomic Energy Commission has been putting large sums of money into the development of nuclear reactors for the production of electricity. If comparable funds had gone into coal R&D there seems no reason to doubt that by now we could have had clean fuel from coal and liquid and gaseous fuels as well. This provides another example of the failure or lack of an energy policy. The AEC did its job in pushing the development of "atomic energy." There was, however, no equally well-financed and determined agency to give a similar push to coal. As a result of its worsening competitive position, our most abundant national fossil fuel resource has been steadily losing its share of the market.

Uranium: The uranium industry is relatively young and is enjoying the benefits of the fact that for some time (until 1970) its only customer was the government. It is even more carefully protected than oil. There is an absolute ban on importation of foreign uranium and the government is only slowly releasing its own $800 million stockpile of surplus uranium in order not to lower domestic prices. As the demand for this fuel grows, we will expect to see it subjected to the true signals from the marketplace.

The Energy Companies

If we look a bit further into the uranium industry, we begin to see familiar faces — the oil companies. In 1970, 17 oil companies controlled 48 percent of the uranium reserves and 28 percent of the uranium ore processing capacity. If we had looked into the corporate structure of coal companies, we would again have found the names of oil companies, for they control perhaps 20 percent of the production and 30 percent of the reserves in this industry. In the past 10 to 20 years, by a series of mergers, expansions, and acquisitions, the oil companies have become energy companies. We can show this in several ways. In Table 7-2 we provide a list of the various energy holdings of the top 25 oil companies (in 1970). We see from this diversification the justification of calling these "energy companies." The largest uranium producer is Kerr-McGee, a relatively small oil company (22 on the list of Table 7-2). The second largest coal producer is Consolidated Coal Company owned by Continental Oil. The overall ranking of the companies, in the terms of total energy supplied (in 1970), is as shown in Table 7-3.

There are reasons both to applaud and decry this dominance of the production of primary energy by a relatively few large firms. Throughout our recent history it has been the increases in the size of our various corporations that have given us "efficiencies of scale" resulting in lowered prices. The big energy company, as well as the big electric utility, automobile manufacturing company, or supermarket, can usually achieve savings, some of which are passed on to the consumer. It is also true that enormous financial resources are now needed to drill for offshore oil, to build supertankers, refineries,

TABLE 7-2

Diversification in the Energy Industries by the 25 Largest Petroleum Companies, Ranked by Assets, 1970

		ENERGY INDUSTRY				
Petroleum Company	Rank In Assets	Gas	Oil Shale	Coal	Uranium	Tar Sands
Exxon	1	X	X	X	X	X
Texaco	2	X	X	X	X	...
Gulf	3	X	X	X	X	X
Mobil	4	X	X	...	X	...
Standard Oil of California	5	X	X	...	...	...
Standard Oil (Indiana)	6	X	X	...	X	X
Shell	7	X	X	X	X	X
Atlantic Richfield	8	X	X	X	X	X
Phillips Petroleum	9	X	X	...	X	X
Continental Oil	10	X	X	X	X	...
Sun Oil	11	X	X	X	X	X
Union Oil of California	12	X	X	...	X	...
Occidental	13	X	...	X	...	...
Cities Service	14	X	X	...	X	X
Getty	15	X	X	...	X	...
Standard Oil (Ohio)	16	X	X	X	X	...
Pennzoil United, Inc.	17	X	...	...	X	...
Signal	18	X	...	...	...	...
Marathon	19	X	X	...	...	...
Amerada-Hess	20	X	...	...	X	...
Ashland	21	X	X	X	X	...
Kerr-McGee	22	X	...	X	X	...
Superior Oil	23	X	X	...	...	...
Coastal States Gas Producing	24	X	...	...	...	...
Murphy Oil	25	X	...	...	...	...

Source: **The Energy Cartel, Who Runs the American Oil Industry,** Norman Medvin (New York: Vintage Books) 1974, pg. 25.

TABLE 7-3

Big Eight Energy Producers, 1970

1. Standard Oil of New Jersey (Exxon)
2. Continental Oil
3. Texaco
4. Gulf Oil
5. Shell
6. Standard Oil of Indiana (Amoco)
7. Peabody
8. Atlantic Richfield

Source: "A Time to Choose," final report of Energy Policy Project, Ford Foundation (Cambridge, Massachusetts: Ballinger) 1974.

and uranium processing plants. Only these large companies have comparable resources.

On the other side of the coin is the difficulty of regulating firms with such potential political influence. They can, and do, for instance, obtain much better information about energy resources on public lands than the less well-staffed government agencies. The diversification of these companies to all energy sources gives them de facto control of energy policy. They can decide which forms to develop and which to neglect. In particular it is not to be expected that they will support the development of less profitable (for them) energy sources such as solar energy or energy from wastes. A National Energy Policy of the next few decades must find some way to harness the strength of these massive companies to national goals.

The Electric Utilities

As we pointed out in previous chapters the electric utilities are somewhat of an anomaly as businesses go. They are, if taken as a group, the largest industry, with capital assets of $125 billion in 1973. It is not, of course, a single industry, but rather 3,500 separate and independent systems which are a mix of investor-owned utilities, publicly owned (mostly municipal) utilities, cooperatives, and Federal agencies. The breakdown of these by type (in 1968) was 405 investor-owned utilities, 2,075 public utilities (nonfederal), 960 cooperatives, and five Federal utility agencies. Most of these utilities (70 percent), however, are engaged in distribution only. This is true of 93 percent of the cooperatives and 66 percent of the public (nonfederal) ones. The generation of electricity is dominated by the investor-owned utilities. The 200 largest investor-owned systems operate 75 percent of the generating capacity, the Federal systems an additional 12 percent. They dominate the sales also; the investor-owned systems serve about 80 percent of the total customers of the electric power industry and the five large Federal utility agencies 13 percent.

Policy has been set in this area only in a piecemeal manner. The state regulatory agencies establish rate structures; the Federal Power Commission (FPC) shares in overall planning, projection, and data collection. The Rural Electrification Agency makes loans to rural cooperatives, etc. The utilities themselves do some joint planning through regional power pools, etc.

For the first three-quarters of this century all of the concerned agencies, from the Federal Power Commission on down, took as their charter some variation on the theme "...assuring an abundant supply of electric energy throughout the United States with the greatest possible economy and with regard to the proper utilization and conservation of national resources."[8] The operative part of the charter has been the first part and the utilities and the supportive agencies have, as we can see from the data of Chapter 4, Volume II, delivered abundant low-cost energy.

As with other energy sectors, however, the utility industry has now reached a point in its growth where it too must examine the "More Is Better" motto. As we pointed out in previous chapters, it is no longer a declining cost industry and the new electric power will, it appears, cost more, in both an economic and environmental sense.

The policy problems faced by the utility industry go throughout the levels of the system. We described in Chapter 6 of this volume some of the suggestions for rate changes which could lead to more efficient use of electric energy. Modification of the promotional rates or "declining block rates" which are designed to encourage consumption is one challenge to utilities, regulatory agencies, and the citizens who control them. We also passed along the suggestion for a rate structure that discouraged use during peak power periods. This also needs analysis.

If the industry is to expand fast enough to keep up with demand it must receive help in other areas, particularly in the area of power plant siting. There is now a gauntlet of hearings, etc., which must be run, and uncertainty dogs the planner's steps. Since it takes five to seven years to design and build a plant, and since electric demand has been doubling every 10 years, the utilities are hard pressed to open new generating facilities fast enough. It has been suggested that long-range and participatory planning for site selection is needed so that the utilities can know in advance what sites are open.

Long-range site planning should probably be done on a regional rather than a statewide basis. In fact, considerations of efficiency suggest that utility systems get larger and that the trend toward power pools and regional planning continue. There are a number of decisions which, it would appear, should be made on a regional basis — some even at the national level. The Four Corners controversy provided an example. It would seem that national input is required into the decision to use coal from a scenic region like this to provide power to Southern California. We have given other examples.

It follows, however, that regional planning and implementation will need regional regulation. The states will be challenged to provide a mechanism for not only regional planning but for consumer input into this planning. Among the choices available to a region, for instance, should be that of getting by on less power. The utilities must also be opened up to competition and cooperation with onsite generation of electricity and with the so-called total power systems.* We must also look for ways to get more research carried out in the utilities (this activity, once virtually nonexistent, has greatly increased) so that they can become partners in the search for alternative energy sources.

The role of the FPC will also be crucial in the decades ahead, especially its planning role. The industry relies heavily on the projections of future demand, but as we say elsewhere (Chapter 4, Volume II) projections in the electric utility area are apt to be "self-fulfilling prophecies." Oversupply was not a serious problem when electric energy was cheap, but each new generating plant now ties up $400 to $500 million in capital and 100 to 600 acres of land — often riverside or coastal land. The future must be much more closely targeted.

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[8] From the Federal Power Act, 16 U.S.C. 824 a (a) Section 202a.

*In such a system a housing area, school, or industry might choose to generate its own electricity and use the waste heat in non-wasting ways.

It's Our Energy

An important fact of energy which also must be added to the calculations for a future energy policy is that most of the future resources of primary energy are owned by the American public. It is our energy. The factual basis of this statement is documented in Table 7-4. On Federal land (and this includes Indian land) are to be found 37 percent of the oil resources, 43 percent of the gas resources, 48 percent of the coal reserves, 81 percent of the richer oil shale, and about 50 percent of both geothermal sources and uranium. Thus, whether we like it or not, the Federal Government, and therefore this nation's citizens are thoroughly involved in the decisions of what to produce, where, and for how much.

Citizen groups have, since 1970, become more active and effective in their efforts to protect the environment from some of the damage caused by Federal as well as private energy-environment decisions. The National Environmental Policy Act (NEPA) has in it a number of requirements for actions to ensure environmental protection. In particular, all major Federal projects are required to develop "environmental impact statements." This applies, for instance, to the Department of the Interior and its resource development plans. To some extent, because of court decisions, impact statements have been produced for the Outer Continental Shelf leasing plan and for oil shale development. Such statements have not been produced so far for coal development or onshore oil or gas leasing.

There is much criticism that the present leasing system is not sufficiently competitive or productive, either of revenue or energy supplies.[9] Without passing judgement on this criticism it does seem clear that the U.S. Geological Survey, for instance, is seriously short of the

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[9] See, for instance, "A Time to Choose," Ford Foundation Energy Policy Project, Cambridge, Massachusetts: Ballinger, 1974, Chapter 11.

TABLE 7-4
Federal Resource Ownership and 1972 Production

	Reserves	Percent of Domestic Total	Resources	Percent of Domestic Total	Production	Percent of Domestic Total
Oil						
(Billions of barrels)						
OCS[(a)]	8.7-10.7	11	58-116	30	0.41	10
Onshore	2.8- 3.3	4	15- 30	8	0,22	5
Total	**11.5-14.0**	**15**	**73-146**	**37**	**.63**	**16**
Gas						
(Trillion cubic feet)						
OCS[(a)]	57.8-76.8	15	355-710	36	3.04	16
Onshore	24.2-31.2	6	75-150	8	1.06	6
Total	**82.0-108.0**	**21**	**430-860**	**43**	**4.1**	**22**
Coal						
(All categories, billion tons)	186.9	48	Not available		10 million tons	2
Oil Shale						
(Billions of barrels oil)						
25 gallons-per-ton shale (10-plus thickness)			480	81		(No commercial production)
15-25 gallons-per-ton shale (15-plus thickness)			900	78		
Geothermal			No breakdown available—approximately 50 percent of domestic total			(No commercial production)
Uranium	1		No breakdown available—approximately 50 percent of domestic total			

Source: "A Time to Choose," final report of Energy Policy Project, Ford Foundation (Cambridge, Massachusetts: Ballinger) 1974, pg. 271.
[(a)] Outer Continental Shelf

scientific manpower needed to enable accurate estimates to be made of the true worth of the various resource-bearing lands. And at the present they do not have routine access to the data obtained by energy company explorations. Our future policy for the development of these publicly owned resources must be based on the best data obtainable. The resource owning public should at least have before it the choice of paying for the energy as they buy it or subsidizing it through lost public revenue.

A Look at the Options

We have so far in this chapter sketched some of the history of energy policy and underlined some of the policy decisions soon to be before us. The clearest message from the past, and a message which should be carried by the various facts we have collected in this Source Book, is that we must at once develop a National Energy Policy. We can no longer be guided simply by "More Is Better."

As a nation we are in the turbulent first steps of that development and change is taking place. Through the past two years the major share of energy planning has fallen to the Federal Energy Administration (FEA). This planning has resulted in a massive report, the "Project Independence Report," which has been mentioned in previous chapters. This report lays out several different paths into the future, requiring differing amounts of energy and different energy-environment decisions to implement them. We will finish this chapter, and this volume, by giving brief descriptions of these options.

Parallel with (but of course independent of) the FEA study, the Ford Foundation sponsored an "Energy Policy Project," which also develops, as examples, three energy options for the immediate future. We will describe them and compare them with those of Project Independence.

Project Independence

The FEA study evaluates four different energy strategies:

A Base Case, which is essentially a continuation of existing policies.

An Accelerated Supply Strategy, which is similar to the optimistic Supply Case I of the National Petroleum Council we examine in Chapter 5, Volume II. It calls, for instance, for acceleration of offshore leasing, opening the Naval Petroleum Reserves to commercial development, and speeding up nuclear plant construction.

A Conservation Strategy, which would reduce demand by some of the tactics we describe in the previous chapter; increasing automobile mileage and residential insulation, for instance.

An Emergency Preparedness Strategy, in which a standby curtailment program is readied (see Figure 6-2, Volume I) and a stockpile of crude oil is built up.

Energy demand and supply are examined under several oil price assumptions, since this seems to be one of the most sensitive factors in the entire energy picture. Most of the projections are made from two oil prices, $7 per barrel, which seems a reasonable figure based on the present situation, and $11 per barrel, a price that was reached during the shortage and one that could perhaps be sustained if the OPEC (Organization of Petroleum Exporting Countries) cut back their production by about 50 percent. We will now look in a bit more detail at each of these four cases, compare their projections with the more traditional (and older) ones of Chapter 4, Volume II, and summarize some of the economic and environmental decisions that must accompany each option.

The Base Case: Even the Base Case, in the new post-embargo energy framework, projects a lower total energy consumption by 1985 than did the earlier projections we summarize in Figure 4-18, Volume II. The total energy consumption and petroleum exports are compared in Figure 7-1 with 1972 levels and with the average of Figure 4-18, Volume II.

It is clear from this data that we would be very near self-sufficiency in 1985 with the higher oil price. Total imports would only be about 6 percent as compared with 23 percent at $7 per bbl world oil prices and 16 percent in 1972. The assumptions and policy decisions, etc., which will be necessary to make the Base Case possible are the following:

Natural gas production will not be discouraged by regulation (or, alternatively, it will be deregulated).

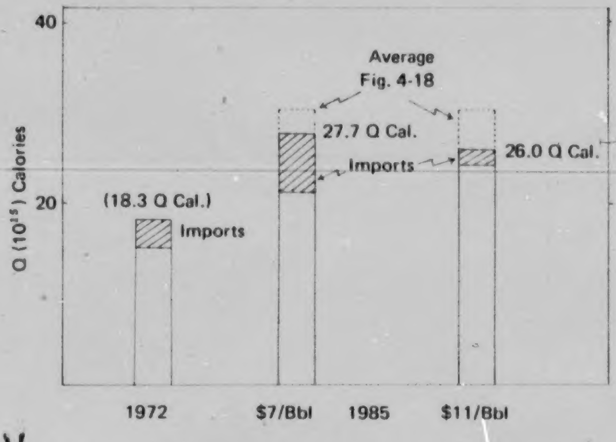
Clean Air Act provisions will be modified to allow existing fuels to be burned.

Tax laws, depletion allowances, profits, etc., will remain unchanged.

Natural gas will be available from Canada at $1.20 per thousand cubic feet and liquified natural gas will be available at $2.00 per thousand cubic feet.

FIGURE 7-1

Base Case Projections at $7 and $11/Bbl Oil



The Trans-Alaskan Pipeline will be completed on schedule.

No new Pacific, Atlantic, or Gulf of Alaska offshore leasing will occur.

In addition to the total energy and import projections, it is interesting to see the economic implications of the two different oil prices. In the first place, at the higher oil price, with lowered imports, we are more secure against interruption. At $11 per bbl oil we would only be importing 3.3 million barrels per day (M bbls per day) and only 1.2 Mbbls per day would be "insecure" (from the Middle East) as compared with 6.2 M bbls per day of insecure imports out of a total of 12.4 M bbls per day at $7 per barrel oil. The cost to our economy of a one-year interruption would be $205 billion at $7 per barrel oil and $40 billion at $11 per barrel oil.

The other economic indicators which were examined are energy cost, the inflation rate, the rate of growth of the GNP, and the outflow of money to buy oil. These are presented in Table 7-5. We see that the more expensive oil raises the price of energy, increases the inflation rate slightly, lowers the rate of growth of the GNP, but reduces the outflow of money by about a factor of three.

There are also environmental costs of the Base Case program but we will postpone their discussion to a final comparison.

The Accelerated Supply Strategy: It is projected that with certain additional actions to facilitate and encourage domestic production, the import deficits shown in Figure 7-1 (23 percent for $7 per bbl oil and 6 percent for $11 per bbl oil) could be reduced to 15.5 percent for $7 per bbl oil and zero at $11 per bbl oil. At $11 per bbl the Accelerated Supply Strategy could make us energy self-sufficient.

The policy considerations necessary for this strategy are:

Speedup of nuclear plant licensing to increase its contribution by 18 percent above the Base Case estimate by 1985.
Opening of Naval Petroleum Reserves to full-scale commercial development.
Significant new oil exploration and leasing offshore on the Atlantic, Pacific, and Gulf of Alaska.
Additional oil and gas pipelines from Alaska.
Development of oil shale.
Federal assistance in obtaining necessary manpower, materials, and equipment.

In the Accelerated Supply Strategy with the high oil price, domestic production would rise, additional oil would be developed in Alaska, oil shale would produce 1 M bbl per day and tar sands, 0.3 M bbl per day. The cost of energy would drop, as would the outflow of money. We will compare all the economic indicators later (see Table 7-6).

The other supply cases: We examine the Conservation Strategy in some detail in Chapter 6. It reduces total consumption (see Figure 7-1) from 27.7 Q Calories ($7 per bbl oil) and 26.0 Q Calories ($11 per bbl oil) to 25.1 Q Calories and 23.8 Q Calories respectively. There are corresponding economic payoffs which we shall compare later.

The fourth strategy, Emergency Preparedness, envisions stockpiling oil against an embargo. Extrapolating from the recent embargo experience projects that an embargo that reduced imports by 1 M bbls per day for a year would cost the economy $33 billion. It is possible to begin a program of buying surplus oil and storing it in steel tanks, at about $2 per bbl per year, or in salt domes (underground cavities roofed with salt — similar to the places oil is found), at about $1.25 or $1.30 per bbl per year. The example given is the following: A one-year interruption amounting to 3 M bbls per day would cost the economy $99 billion. To store enough oil in 10 years to ward that off would cost $19 billion. Thus if the odds are as high as 1 in 5 that such an interruption will occur, it would pay to begin a storage program.

The Project Independence Projections—A Comparison

We have briefly reviewed the assumptions and some of the projections of each of the Project Independence strategies. We will now look at the important consequences of each of the four major strategies: the Base Case, the Accelerated Supply Case, and the Case of each of these with Conservation.

The total energy and import projections are shown in Figure 7-2. We see that at $7 per bbl oil the combination of Accelerated Supply and Conservation cuts the import deficit to a manageably small amount (5.6 percent) while at $11 per bbl oil, even smaller imports are required. Either the Accelerated Supply, or its combination with Conservation, can make us entirely energy self-sufficient.

The projections of the economic indicators are also of interest and we show them in Table 7-6. As far as these data go, the economic advantages seem to favor Accelerated Supply plus Conservation. Domestic energy costs less, the dollar outflow is less, and vulnerability to embargo is less.

It is also of interest to look at the sources of energy under the different strategies for these give strong clues as to the type of environmental impact expected. These

TABLE 7-5
Economic Impact of Base Case, 1985

Indicator	$7	$11
Domestic Energy Cost	$5.15 per M Cal.	$5.55 per M Cal.
Inflation Rate (1973-1990, CPI)	6.2%	6.4%
Average Annual Growth in GNP (1973-1985)	3.7%	3.2%
Annual Outflow of Funds from U.S. in Payment for Oil	$31.7 billion	$13.2 billion

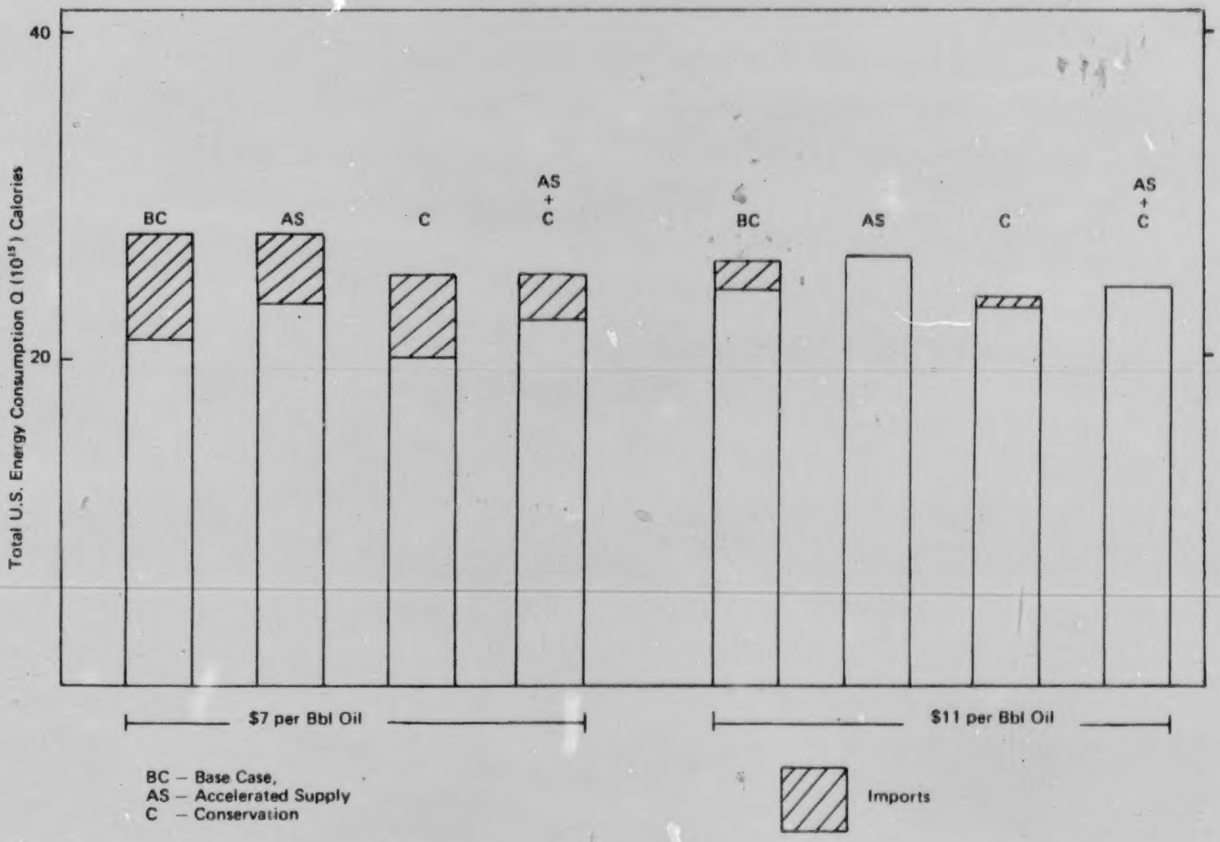
Source: "Project Independence Report," Federal Energy Administration, November 1974, pg. 31.

TABLE 7-6
Economic Results of Various Strategies

Indicator	BC	AS	C	AS+C
$7 Per Bbl Oil				
Domestic Energy Cost (1985)	$5.15 per M Cal.	$4.90 per M Cal.	$4.85 per M Cal.	$4.65 per M Cal.
Inflation Rate (1973-1990)	6.2%	NA	NA	NA
Annual Growth of GNP	3.7%	NA	NA	NA
Dollar Outflow for Oil (1985)	$31.7 Billion	$21.8 Billion	$25.0 Billion	$14.3 Billion
Cost of 1 Year Interruption	$205 Billion	$149 Billion	$172 Billion	$99 Billion
$11 Per Bbl Oil				
Domestic Energy Cost (1985)	$5.55 per M Cal.	$4.95 per M Cal.	$5.05 per M Cal.	$4.50 per M Cal.
Inflation Rate (1973-1990)	6.4%	6.3%	NA	NA
Annual Growth of GNP	3.2%	3.2%	NA	NA
Dollar Outflow for Oil (1985)	$13.2 Billion	0	$4.8 Billion	0
Cost of 1 Year Interruption	$40 Billion	0	0	0

Source: "Project Independence Report," Federal Energy Administration, November 1974, Chapter 6.
NA - Not Available.
BC - Base Case, AS - Accelerated Supply, C - Conservation.

FIGURE 7-2
Comparison of Forecasts for 1985



are summarized for 1985 in Table 7-7. A close reading of this table gives hints of the futures open under the several options. The Base Case (business as usual) uses oil and gas over coal when oil is in the lower price range and likewise Conservation saves these two preferentially over coal. At the low oil price, the efforts to increase domestic supplies (the Accelerated Supply Case) are directed mostly to natural gas and to nuclear energy which increases at the expense of coal.

With oil at $11 per bbl the priorities change. In the Base Case, coal is used in preference to oil and production goes over a billion tons per year. Natural gas production also increases a little. The Accelerated Supply Strategy produces a little more oil and gas as more expensive domestic extraction techniques become economically feasible. Nuclear power is again called on to make its maximum feasible contribution. Conservation, again, is mostly saving of oil and gas.

The complimentary picture to Table 7-7 is provided by Table 7-8, which summarizes the environmental impacts of the three energy strategies and compares them with the 1972 data. Many of the 1985 impacts are less than 1972 due to the anticipated improvements in pollution control. Nonetheless, the heavy reliance on coal (Table 7-8 is based on $11 per bbl oil) increases solid waste and land disruption and the increase in the nitrogen oxides, NO_x, is also obvious.

There are, of course, many environmental factors not considered here. In the Accelerated Supply Case oil spills are reduced as oil imports are replaced by domestic production, but solid waste is increased by oil shale mining as the now virgin areas of Colorado, Utah, Alaska, and the Outer Continental Shelf are mined or drilled for energy. The social impact and others that we looked at in Chapter 2 also must be considered. The Conservation Strategy, of course, has, as expected, the least environmental impact.

From even this brief summary of the Project Independence projections we can draw several conclusions. Even without deliberate conservation strategies the higher energy prices are expected to bring consumption below the earlier predictions. Utility electricity, in particular, which the consensus of Figure 4-21, Volume II, shows as 3,800 B kilowatt-hours, is reduced somewhat. At $11 per bbl oil and with conservation the reductions below earlier predictions are quite significant.

There is much more that could be said about the details of this report, but our lack of space requires that we leave it to the reader to translate millions of barrels of oil saved into fewer tankers or offshore wells, millions of tons of coal into acres strip mined, etc. The data for such conversions are in this Source Book.

The Ford Energy Policy Project

The three-year, $4-million study of energy policy by the Energy Policy Project funded by the Ford Foundation has added much necessary data and projection to our too-scant store. Its results, which are still being published at this writing, are also too broad to summarize satisfactorily. We have examined some of its projections and study results elsewhere in the Source Book. We will concentrate here on the three energy projections that are the focus of the final report, "A Time to Choose."

The Historical Growth Scenario, which is their version of business as usual.

TABLE 7-7
Projected Fuel and Energy Consumption Under Various Strategies for 1985

	BC	AS	BC+C	AS+C
$7 per Bbl Oil				
Coal (M tons)	866	762	713	635
Petroleum (M bbls)	8,730	8,666	7,729	7,506
Natural Gas (B ft³)	23,205	23,976	21,817	22,889
Nuclear Power (B kw-hrs)	1,251	1,471	1,251	2,471
Utility Electricity (B kw-hrs)	(3,724)	(3,692)	(3,370)	(3,341)
Total (Q Calories)	**27.6**	**27.7**	**25.1**	**25.2**
$11 per Bbl Oil				
Coal (M tons)	1,005	918	850	700
Petroleum (M bbls)	6,989	7,005	6,171	6,536
Natural Gas (B ft³)	24,007	24,873	22,943	23,970
Nuclear Power (B kw-hrs)	1,251	1,471	1,251	1,471
Utility Electricity (B kw-hrs)	(3,615)	(3,559)	(3,250)	(3,197)
Total (Q Calories)	**26.0**	**26.2**	**23.8**	**24.2**

Source: "Project Independence Report," Federal Energy Administration, November 1974, Chapter 6.

( ) - Not added into totals.
BC - Base Case, AS - Accelerated Supply, C - Conservation.

TABLE 7-8
Environmental Impacts of Energy Strategies (Selected Indicators)

		1985 at $11 Oil Imports Alternate Energy Strategies		
Air Pollution	**1972**	**Base Case**	**Accelerated Supply**	**Conservation**
Particulates (tons per day)	1,800	2,200	2,300	1,800
NO_x (tons per day)	30,000	46,800	43,000	38,400
SO_x (tons per day)	58,900	53,700	48,800	41,500
Water Pollution				
Dissolved Solids (tons per day)	37,000	5,800	5,500	5,000
Suspended Solids	7,600	300	260	210
Solid Waste				
1,000 Tons per Day	900	1,100	2,300	900
Land Disruption 1,000 Acres	19,800	26,700	21,800	17,900

Source: "Project Independence Report," Federal Energy Administration, November 1974, pg. 40.

The Technical Fix Scenario, in which improved efficiency of energy-utilization and other conservation schemes are expected to lower growth.

The Zero Growth Scenario, which examines the possibility of slowing energy growth to zero by 1990 and holding it constant after that.

We show the energy consumption projections of all three of these scenarios in Figure 7-3 and for reference have added some projections for 1985 from Project Independence (we only show four of eight points in Table 7-7 since the others are almost identical).

As one might expect, there is considerable similarity between the Energy Policy Project (EPP) Historical Growth Scenario and the Project Independence (PI) Base Case. The PI Base Case projects lower energy consumption so that it becomes an S-curve (this S into it, whereas the EPP scenario projects historical rates of growth.

The EPP Technical Fix Scenario is also quite similar to the PI cases with conservation, although the EPP projection is a bit more optimistic about the amount of energy which can be saved.

The unique contribution of the EPP study is the Zero Growth Scenario. We will spend a few words in a more detailed description of how energy growth might be brought to zero and what the consequences of that dramatic change in our energy consumption trajectory might be.

An energy S-curve: In the terms of the discussion of growth in Chapter 4, Volume II, what is being proposed here is a turnover of the exponential growth in energy consumption so that it becomes an S-curve (this S shape can be distinguished in Figure 7-3). The questions to be answered are: Why? How? and What Happens? Why is it proposed that the growth in energy consumption slow to zero? How can this be accomplished? What will consequences be in each of the sensitive sectors of our lives?

The "Why?" is the easiest one. All we have said in this volume should suggest that our problems are intimately associated with energy consumption growth and that we have a better chance of solving them if that growth is slowed. Then we can choose more freely among the controversial primary energy supply options, the pollution problems will be lessened, we can reduce imports and free oil for other markets, easing international tensions, etc.

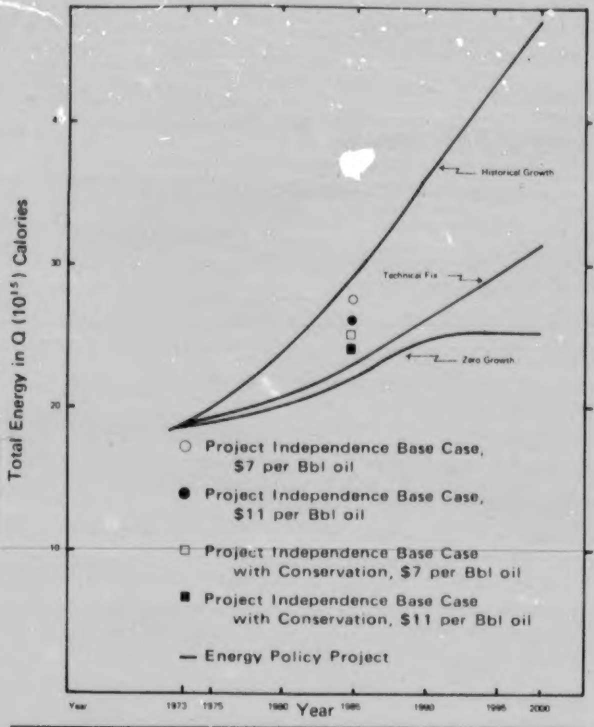
How shall we do it? Slowly and with careful planning is the first part of the answer. We have already suggested some of the energy-conserving steps which can be taken. The major targets are transportation, in which a determined effort would be made to reduce our employment of energy-inefficient forms of transport, and housing, in which tightened building and lighting codes would save energy. Along with these energy-saving strategies, the EPP suggests the elimination of depletion allowances on virgin oil, etc., and the end of discriminatory freight rates so that recycling is encouraged. The Federal Government would be expected to step up energy R&D, especially that part of it aimed at improving the utilization of energy.

The major and most controversial policy change suggested is for an "energy tax" on all energy consumed which would grow from 3 percent of the retail price in 1985 to 15 percent by 2000. There are a variety of ways in which this tax could be imposed, but its aim is to put marketplace pressure behind energy conservation. The revenues collected could be used to further the energy-saving goals by improving the mass transport system and by supporting needed low-energy services like health care, education, law enforcement, etc.

What will the consequences be? One can expect improvements in the environmental area. The real worry is in the economic area. What about jobs? What about economic growth? We discussed, in Chapter 6, some reasons behind the belief that neither employment nor the GNP need be drastically affected. In a society where energy-intensive industrial practices become much more expensive we might even expect an increase in employment. The GNP is also projected to grow at nearly the same rate as under other strategies. As we showed in Figure 5-4, the EPP projection is that the year 2000 GNP in the Zero Growth Scenario is only 4 percent less than in the Historical Growth Scenario even though

FIGURE 7-3

Comparison of Ford Energy Policy Projections with Project Independence



Data from: "Project Independence Report," Federal Energy Administration, November 1974, and Ford Energy Policy Project.

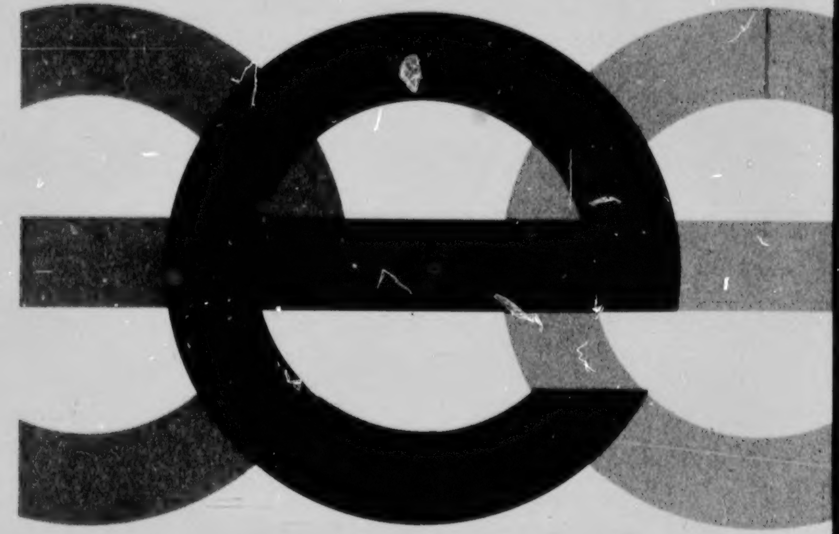
the total energy use in the latter scenario is almost double the former. The EPP projection is that there will be a slight shift, of 1 percent, from goods to services as energy production and the production of energy-intensive goods slow down. It is their firm belief, and a finding of their study, that economic growth and energy consumption growth can be uncoupled.

On to 1985

These then are the options presented to us as we hesitate at the crossroads of energy policy. There is not much more to say. We have tried to summarize the data where it exists and evaluate the effects of changes in energy policy at all those points where the energy web connects to our environment and our society. We have described where our present energy comes from and where the energy of the future may come from. We have underlined those energy supply decisions which seem to us the most controversial: offshore and Alaskan oil drilling, increased oil importation, Western coal mining, nuclear energy (the breeder reactor in particular), and oil shale development. We have finally, in this chapter, looked briefly at energy policy and policymakers in each of the major fuels and energy areas and have finished with a description of the latest in the series of options for the future which have been put before us.

We end this volume as we began it. The decisions now before us in this country, and in the world, are surely the most important ones faced in this century. It is often thus at the end of an era, and we have come to such an end. The responsibility for decision making, in the final analysis, resides with citizens. Thus the teacher-readers of this Source Book have a dual challenge, as citizens and as molders of citizens. What we have tried to do is lighten the educational task by gathering in one place as much of the background data, conjecture, and projection as we could. We leave the rest to you.

ENERGY-ENVIRONMENT SOURCE BOOK



Volume 2

Energy, Its Extraction, Conversion, And Use

CHAPTER 1
Energy: What It Is, What It Does

Energy: What It Is, What It Does

"A rose is a rose is a rose" is a definition of a rose only to someone who has seen these flowers. We can do little better in talking about energy; we can only define it to someone who already has some idea of what it is.

There are, of course, scientific statements we could make about energy, about its relation to such other scientific concepts as force, work, and power, or about the laws that govern it. We will, however, take a bare minimum of words from the vocabulary of science, only those needed to understand the twin crises of energy and environment. We will begin the story with "energy is energy."

Energy Is

It is not possible to be unaware of energy; it forces itself to our attention from all parts of our life. Newspapers and magazines carry articles about the Energy Crisis and the ways we are moving to meet it. Television carries advertisements about oil exploration and documentaries about strip mining on the Western Plains. There is an image of energy in the smoke from a power plant or a steel mill, in the transmission lines along the road or the oil truck on it. There is energy in the electric toaster and in its hot buttered toast. Energy is defined to us in all these ways and many more.

> *Whenever we have heat, or light (or the other forms of radiation: radio, x-rays, ultraviolet, etc.), or motion, we have energy in action. Whenever we have something, such as a lump of coal, a battery, or a piece of uranium, that can ultimately provide us with heat, light, or motion, we know that energy is stored in that something.*

When faced with such diversity, our first step toward understanding is to set up categories, to reduce the diversity of form that energy shows by classifying it. We have already suggested the first classification. Energy in the form of motion, heat, or light is called *kinetic energy*. The energy stored in bread, gasoline, or batteries, in the nucleus of the uranium atom, or in any of its other clever hiding places, is *potential energy*. Kinetic energy is energy in transit, energy on the move. We *use* it in this form. Potential energy is *stored* energy and it is in this form that we dig it from mines, pump it from wells, ship it, and stockpile it. The whole story of energy is found in the description of these two forms, and in the conversions between them.

To *use* energy it must be in the kinetic form. We use energy because we want to *do* something to matter: move it, illuminate it, or warm it. A moving car has kinetic energy. The electrons flowing through the toaster's heating element and the photons of light coming to us from the sun have their energy in kinetic form.

We *store* energy in the potential form. It is, of course, possible to store kinetic energy; the flywheel of an engine stores kinetic energy in its rotating mass and kinetic energy is stored in the rotation of the moon about the earth. We can, also, store heat energy in Thermos bottles. Light energy is almost impossible to store. Kinetic energy storage, however, is quite different from potential energy storage. It is temporary; we trap or insulate kinetic energy, it is a caged tiger ready to run free.

Potential energy storage is more permanent. It is accomplished within the structure of matter. Energy is stored, for instance, in the carbon atom and released when that carbon atom is combined with an oxygen molecule in the chemical reaction we call burning. The product of this reaction is carbon dioxide, CO_2. The nucleus of the uranium atom stores energy that is released when that nucleus is split in two in the fission reaction. A simple way to store energy is to lift something away from the earth. Energy is stored when water is pumped to the top of a water tower, then converted to the kinetic energy of motion when the water is allowed to run through the pipes to its final destination. In general, to store energy we must move things around against the action of some force, lift a weight, force electrons into a battery or compress a spring, for instance.

The Energy Laws

From what we have said so far, it should be becoming clear that the story of energy is one of flow and change. Energy is not really like a flower, but like a chameleon; it has a basic identity but constantly changes form. It can be potential energy stored in coal, but when the coal is burned in a power plant furnace, it changes to a kinetic form, the heat energy of steam. When the steam is allowed to strike the blades of a turbine, some of this heat energy becomes the kinetic energy of motion of this engine. The turbine turns an electric generator and some of the same energy that was released from the coal becomes electric energy, the kinetic energy of the motion of electrons in wires. And still the flow doesn't end; electricity goes out through the wires to perform a great variety of tasks, from running the turntable of our stereo to making ice cubes in the refrigerator.

These changes of form are not free or arbitrary, they are governed by strict laws. The first of these is quite reassuring; it seems to say that there can't be an Energy Crisis. Called the Law of Conservation of Energy (or the First Law of Thermodynamics, if you want a fancy name) it states:

> *Energy can be neither created nor destroyed.*

This says that once you have a certain amount of energy, the 200 Calories you get from eating a candy bar, for instance, it never disappears. It may become heat energy in your body, or power your muscles, or be used in the processes in your brain. It may be stored as fat. More likely, it does some of all these things all at once, but it always remains 200 Calories of energy.

This first law is good news. We can never run out of energy. Where then is the problem? The second law, which is named "The Second Law of Thermodynamics," but which we'll call "The Heat Tax," gives the bad news:

> *In any conversion of energy from one form to another some of it becomes unavailable for further use.*

It becomes unavailable because it becomes heat and it is not possible to convert a given amount of heat energy completely back into another form. Said in another way, in any conversion or use of energy there is a "heat tax"; some of the energy becomes heat and is no longer usable. This unusable heat energy leaks away and gradually warms up the earth (and finally the universe). It is this second law that is behind the Energy Crisis.

It is also clear that this second law puts heat energy in a unique position. It is possible to convert all of a certain amount of mechanical energy to heat, by rubbing two sticks together or putting on the brakes of a car, for instance. It is possible to convert all the chemical energy of coal into heat energy by burning it. These conversions cannot go to completion in the other direction, however. In the language of science they are "irreversible." Heat energy stands at the end of a one-way street, all other energy forms ultimately can be converted into heat, but only a limited amount of heat energy is convertible back to other forms.

We are only skimming some interesting science with these statements. Why do we believe these laws? What is the nature of this strange energy we call heat? How can we convert heat energy to mechanical energy? We answer some of these questions more fully in Appendix 4. For now we must get on with our story and look at energy from the narrow perspective of man.

Energy, Work, and Power

So far we have defined energy by asking you to observe it around you as light, motion, or heat, or as the capacity to produce these conditions. There is another word, *work*, that is associated with energy. It is used to describe man's use of energy in mechanical form: transporting things, rearranging, or distorting them. We do work when we lift a weight, push a cart, pull back a bowstring, or swing a golf club. Work, therefore, is the same as energy—it is mechanical energy in use.

Power: A second term associated with man's energy-consuming activities is power. We talk of the power of a car or a motor or a stereo amplifier. As we look deeper into this concept, we find that time is involved in its definition. Power is the *rate* of doing work, or, more generally, the rate at which energy is used. In mathematical terms, power is the amount of energy used (or work done) divided by the time it takes to do that work. In symbols

$$P\ (\text{power}) = \frac{W\ (\text{work})}{T\ (\text{time to do the work})}$$

We also see from this that W (work) = P (power) × T (time).

Work and power play different roles in our discussions. We use work terms to describe things that must be done and for which time is not important. It takes a certain amount of work (or energy) to lift a box, melt an ice cube, or refine aluminum. Power enters when we are dealing with continuous input (or output) of work; with lightbulbs or automobiles, for instance.

When we buy gasoline, we are buying energy and, ultimately, work. We pay for the work to get the car from City A to City B. When we bought the car, however, we bought power. We paid for the horsepower of the engine which determines how fast it can burn the gasoline and thus how fast it can do the work, how quickly it can get us from City A to City B.

Units

We are defining energy by describing it. The final step in this definition is measurement, and to report a measurement we need units — feet, seconds, pounds are familiar ones.

There are many different units for work and power. They were defined for different purposes at different times. The "horsepower," for instance, an old unit, is the rate at which a horse can perform work for an extended time. The kilowatt, a newer electrical unit, is defined in terms of electric current and voltage. There is a similar range of choices for energy and work.

In Appendix 3 we define all of the commonly-used units of energy (work) and power. We also provide there the rules and numbers for converting from one unit to another. In this section we introduce and define only those units that will be in our basic vocabulary for this Source Book.

Since work and energy are interconvertible, a wide variety of choices of units is open to us. We will use the *Calorie*, with a capital C (in scientific terminology the kilocalorie), which originated as a unit of heat energy. It is the amount of work (or energy) necessary to raise the temperature of one kilogram (2.2 pounds) of water, 1°C, (degree centigrade, or *Celsius*, which is the preferred terminology). It is also the same unit we use to measure the energy value of food; the normal dietary intake is 2,000 to 3,000 Calories per day. Calories are based on the kilograms and degrees Celsius of the metric system, and since the United States is reluctantly, but inevitably converting to this universal system, it seems a reasonable choice.

The unit of power most frequently used in the Source Book is the electrical unit, the *kilowatt*, as electricity is becoming our most important form of power. A kilowatt (kw) is one thousand watts, about the amount of electric power needed to provide the heat for an electric toaster. The definition of the watt is developed in Technical Appendix 3. Since power is work divided by time, we can produce a work, or energy, unit, by multiplying a unit of power by time. Occasionally we use a unit derived in this way, the kilowatt-hour (kw-hr), to measure electric energy.

Numbers and Sizes

The other troublesome aspect of our quantitative descriptions of energy and power is that we have to deal with a broad range of numbers, from the 100 watts of the lightbulb, for instance, to the approximately 400,000,000,000 watts (400 billion watts) that is the present total generating capacity of this country. We will work with millions of tons of coal, billions of barrels of oil, trillions and even quadrillions of Calories. To keep this terminology as simple as possible we abbreviate these numbers in the manner shown in Table A2-1 of Appendix 2; a million is M; a billion, 1,000,000,000, is B; a trillion, 1,000,000,000,000, is T; a quadrillion, 1,000,000,000,000,000, is Q, etc. We discuss these large numbers a bit more in Appendix 2.

In Tables 1-1 and 1-2 we show some details of this range of sizes. Table 1-1 shows some of the reference points on an energy scale that stretches from the incomprehensibly small energies involved in molecular events to the equally incomprehensibly large numbers that measure earth's daily income of solar energy. Table 1-2 presents similar reference points in a power range stretching from a hummingbird's power up through the SST and, finally, to a similar ultimate, the incoming solar power. It is often necessary to compare quantities whose growth takes them from the thousands to the billions, this leads us to the "semilogarithmic" presentation of data we will introduce in Chapter 4 and also discuss in Technical Appendix 2.

The Flow of Energy on Earth

With regard to food, mineral resources, air, and water, earth is a spaceship entirely on her own. She carries much of her energy with her, but, fortunately, there is a Mothership, sun, that beams in a fresh energy supply every day. Earth's energy resources, therefore, are a mixture of stored, potential energy, and transient, kinetic energy. There are two basic questions to ask: What are the forms of energy available to us? What are their relative amounts? We will focus on the first of these questions in this chapter and leave the assessment of the resource size to Chapter 2.

Figure 1-1 gives the quantitative information that allows comparison of the various flows of energy (power) to and from earth. We also indicate the two depletable sources of energy, the fossil fuels and nuclear energy. The flow from Mothership sun dwarfs all others; at the top of the atmosphere, the earth receives 173 trillion kilowatts, 173 T kw, of power. For comparison, the total electric generating capacity of the world in 1968 (the last figure available) was about 900 M kw, only 1/200,000 of the power we receive from the sun.

Of course not all of the sun's energy is available to our purposes. As we see from Figure 1-1, 30 percent of this is immediately reflected by the atmosphere, and another 47 percent is absorbed by the atmosphere, the oceans, and the land, and then reradiated. All in all, about half of the total power reaches the ground. Most of the power that is not absorbed and then reradiated, 40 T kw, or 23 percent of the total, is used to evaporate water, providing the energy for the important water cycle of earth. The rest of the processes use less than one percent of the total. The impressive power of wind, waves, and ocean currents is not so impressive when measured against these totals; 370 B kw are used on the average in this way, 0.5 percent of the total. The power used to sustain life is, on this scale, miniscule; 40 B kw at the most, an almost negligible 0.04 percent of

TABLE 1-1
Some Representative Energy Data

	Calories
Energy in 1 Photon of Ultraviolet Light (λ = 2250Å)[a]	21.2×10^{-23}
Energy (gravitational) of 1 Pound of Mass 1 Mile Above Sea Level	2
Energy To Melt 1 Pound of Ice (at 0°C)	36
Energy To Evaporate 1 Pound of Water	245
Energy (chemical) Released by Exploding 1 Pound of TNT	520
Energy (chemical) Released by Burning 1 Pound of Wood	1,250
Energy (chemical) Released by Burning 1 Pound of Sugar	1,860
Energy (chemical) Released by Burning 1 Pound of Coal	3,300
Energy (chemical) Released by Burning 1 Pound of Gasoline	4,750
Energy Needed To Manufacture an Automobile[b]	5,200,000
Energy Needed To Send Apollo 17 To Moon[c]	1,420,000,000
Energy (nuclear) Released by Fusing 1 Pound of Deuterium	32,000,000,000
Energy (nuclear) Released by Fission of 1 Pound of U^{235}	137,000,000,000
Energy Equivalent of 1 Pound of Mass ($E=mc^2$)	9,800,000,000,000
U.S. Daily Energy Consumption (1970)	47,000,000,000,000
World Daily Energy Consumption (1970)	140,000,000,000,000
Energy Needed To Boil Lake Michigan[d]	400,000,000,000,000
Solar, Earth's Daily Total at Top of Atmosphere	3.6×10^{18}
World Supply of Recoverable Fossil Fuels[e]	5.0×10^{19}
Sun's Daily Output	7.8×10^{27}

[a] λ = wavelength, Å = angstrom, 10^{-11} meters.

[b] R. Stephen Berry, "Recycling, Thermodynamics, and Environmental Thrift," **Bulletin of the Atomic Scientist**, May 1972.

[c] Courtesy Marshall Space Flight Center.

[d] 5.8×10^{12} kg. raised from 25°C to 100°C.

[e] M. King Hubbert, "The Energy Resources of the Earth," **Scientific American**, 224, 61, September 1971.

the incoming energy. Even this small number is, however, 40 times as large as the total generating capacity of the world we quoted earlier.

Measured against this munificence, the nonsolar sources of energy seem puny. There are four. Some of the sun's energy has been stored as chemical potential energy in the fossil fuels—coal, oil, and natural gas. The estimated maximum size of the fossilized carbon is about 7,000 Q kilograms. At the 8 Calorie per kilogram of energy released in combustion, this would produce a total of 56,000 Q Calories, which (by the conversions of Calories to kw-hr of Table A3-2) is equivalent to 65 Q kw-hr. By burning all of the fossil carbon, formed over millions of years, we would produce only as much energy as the sun sends in during 15½ days. This value, 65 Q kw-hr, is, of course, an upper limit; it represents all of the fossil carbon and only a small fraction of that, a ten-thousandth or less, is actually available to us. In our burning and conversion we lose much of this energy. We will come back to this number in a later section.

More than 90 percent of the energy that powers our economy comes from burning fossil fuels. In addition to this chemical source of potential energy, there are three others that we show in Figure 1-1: geothermal energy (energy whose source is the earth's molten interior), the energy of the tides, and the new source, nuclear energy. The total power leaking from the earth's interior is only 32 B kw, one five-thousandth of the incoming solar energy, while tides and tidal currents provide only 3 B kw, one fifty-thousandth of the solar input.

The primary sources of energy available to us on earth are, therefore, five: *solar, chemical, geothermal, tidal,* and *nuclear*. Three of these — solar, geothermal, and tidal — are in kinetic form, the other two — the chemical energy of the fossil fuels and nuclear energy — are stored potential forms. We will briefly discuss each of these in the sections that follow.

Solar energy: Solar energy is kinetic energy. It is, more precisely, radiant energy, much of it in the form of visible light. What arrives at the top of the atmosphere is about half ultraviolet radiation — the invisible blue radiation that gives us sunburn — and half visible light. When solar radiation enters the atmosphere, several things can happen. It can be reflected, and as we see from Figure 1-1, 30 percent of this energy is immediately reflected back into space. It can be absorbed by the molecules of the atmosphere, the ocean, or the land surface and increase their energy. This added energy heats them, some of it is reradiated away and lost, some goes into the kinetic energy of their motion. The solar energy that gets to the earth's surface is the important part for us. It heats the land and the ocean and is the source of energy for the great currents, the winds and the waves, in air and ocean.

Man gets some of his energy from the motion of wind and water. The sun's energy evaporates water which rises and is carried on the winds. If it falls on the mountains, we get some of it for our use by letting the mountain-fed streams and rivers turn the turbines of hydroelectric plants. In this example we have solar kinetic energy being converted to heat energy, then to gravitational potential energy as it is lifted, then to mechanical energy as it runs back down the mountainsides, and, finally, to electric energy as it is converted by the generator the turbine turns. In a much less important way, we also use converted solar energy with windmills and sailboats. Here the conversion route is light energy to heat energy to mechanical energy.

The other important way in which radiation interacts with matter is chemically. If radiation of the proper energy strikes a molecule, it can cause molecular rearrangements — chemical reactions — to take place. One of these, the production of ozone at the top of the atmosphere, protects life on earth's surface. The other, photosynthesis, fuels life.

Ozone is formed when solar radiation splits an oxygen molecule into two oxygen atoms. One of these atoms then combines with another molecule of oxygen to form O_3, ozone. This molecule strongly absorbs ultraviolet radiation. The O_3 layer at the top of the atmosphere thus acts as a protective layer against this energetic radiation which otherwise would arrive at earth's surface in lethal amounts.

Photosynthesis is a more familiar reaction. We can describe what takes place in the following way:

$$\text{Carbon dioxide } (CO_2) + \text{Water } (H_2O) + \text{Energy} \rightarrow \text{Carbohydrates } [C_x(H_2O)_y] + \text{Oxygen } (O_2)$$

TABLE 1-2
Some Representative Power Data

	Kilowatts
Bird Flying (hummingbird)[a]	0.007
Human at Rest	0.017
Dog Running Fast[a]	0.06
Fish Swimming (dolphin)[a]	0.21
Human Walking at 2 mph	0.23
Horse Working Steadily (one horsepower)	0.75
Human Running	0.93-1.2
Human (top athletic performance)[a]	1.7
U.S. Per Capita Power (1973)	11.3
Automobile at 60 mph[b]	29.3
Automobile at Top Acceleration[c]	100
Bus[d]	150
Commuter Train[d]	3,000
707 Jet[d]	21,000
SST[d]	180,000
Fossil Fuel Consumption in Urban Area (per square mile)[e]	625,000
U.S. Electric Power Consumption (1973 average)	7,350,000
World Total Power Consumption (1970)	6,000,000,000
Solar Power Involved in Photosynthesis	40,000,000,000
Incoming Solar Power (total)	173,000,000,000,000

[a] "Locomotion: Energy Cost of Swimming, Flying, Running," Schmidt-Nielsen, Science 177, 222 (1972).

[b] A 5,000-pound car uses 39 H.P. under average conditions at 60 mph, Thomas C. Austin, EPA, private communication.

[c] A 4,735-pound automobile accelerates to 60 mph in 11 seconds.

[d] "Lost Power," Environment, April 1972.

[e] The 1970 National Power Survey, Federal Power Commission.

The carbohydrate molecule, whose general formula we give, is an important part of plant life. Ordinary sugar, for instance, is a carbohydrate whose formula is

$$C_{12}(H_2O)_{11} \text{ (with } x = 12 \text{ and } y = 11\text{)}$$

The process of photosynthesis is one, therefore, which converts radiant energy to chemical potential energy. The energy stored in the carbohydrate can be released by burning it (or in chemical terms, oxidizing it). This reaction is the reverse of the one above:

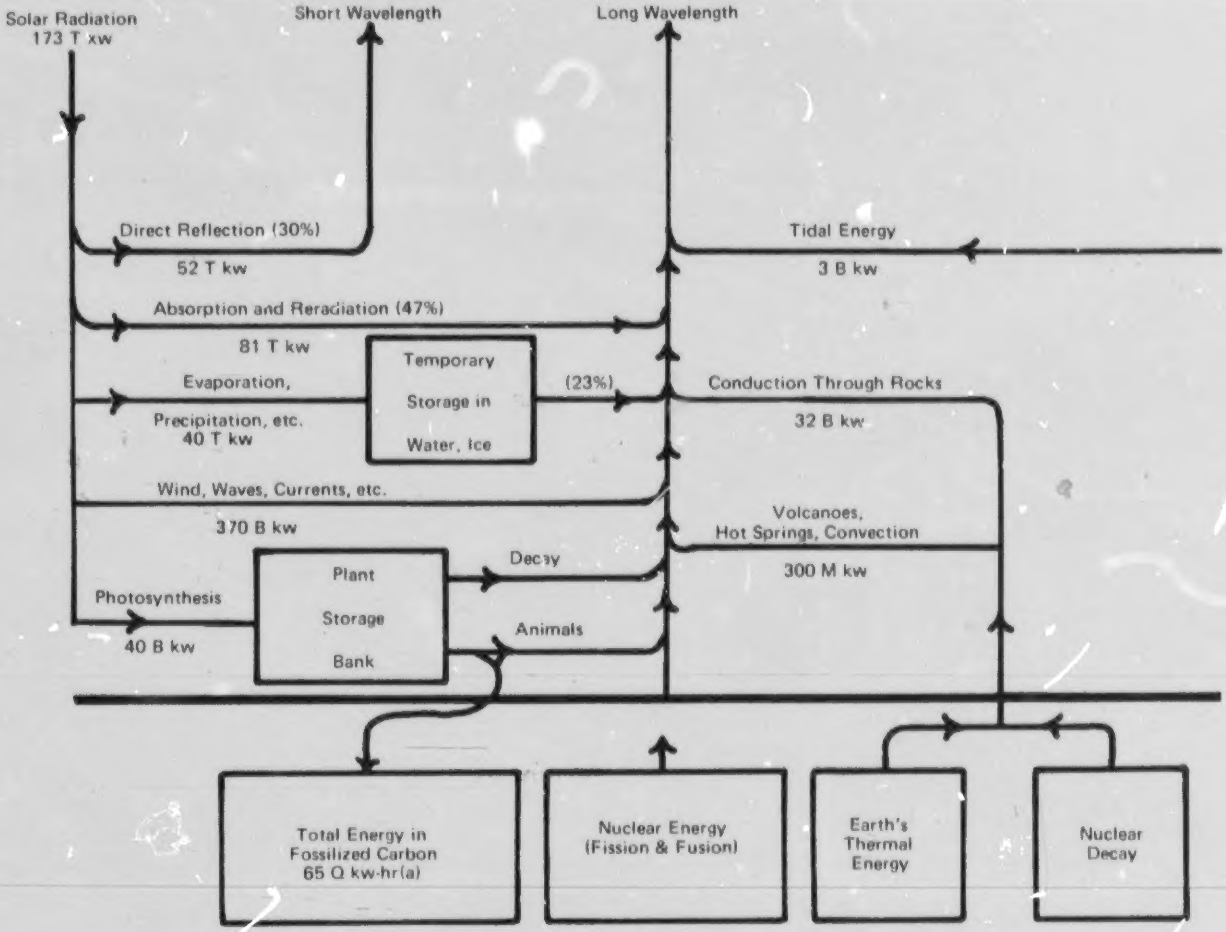
$$\text{Carbohydrate} + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$

Photosynthesis is the source of the food energy we depend on. It is also the source of the chemical energy that was stored in the swampy jungles of ancient earth and formed the fossil fuels—coal, oil, and natural gas. When we burn these fuels we are using stored solar energy.

We should not leave our brief discussion of solar energy without mentioning its source. The sun's energy is "thermonuclear" in origin. The sun's interior is hot enough that a "nuclear reaction" takes place. Bare hydrogen nuclei, protons, stripped of their atomic electrons by countless collisions, combine (fuse) to form helium. In the process some of the mass of the hydrogen is converted into energy; it is this energy converted to radiant form which travels the 93 million miles to earth.

Only a small fraction reaches earth, of course. The sun radiates in all directions and only 4 parts in 10 billion of the total power emitted reaches earth. But this is

FIGURE 1-1
Power Inputs to Earth


Solar Radiation
173 T kw
Short Wavelength
Long Wavelength
Direct Reflection (30%)
52 T kw
Tidal Energy
3 B kw
Absorption and Reradiation (47%)
81 T kw
Temporary
Storage in
Water, Ice
Evaporation,
Precipitation, etc.
40 T kw
(23%)
Conduction Through Rocks
32 B kw
Wind, Waves, Currents, etc.
370 B kw
Volcanoes,
Hot Springs, Convection
300 M kw
Plant
Storage
Bank
Decay
Photosynthesis
40 B kw
Animals
Total Energy in
Fossilized Carbon
65 Q kw-hr(a)
Nuclear Energy
(Fission & Fusion)
Earth's
Thermal
Energy
Nuclear
Decay

Q = Quadrillion, 1,000,000,000,000,000
T = Trillion, 1,000,000,000,000
B = Billion, 1,000,000,000
M = Million, 1,000,000

(a) This is an energy unit, power times time.

Data from M. King Hubbert, "The Energy Resources of the Earth," **Scientific American 224, 62-63, September 1971** plenty; the 173 T kw shown in Figure 1-1, if stored for 24 minutes, could provide for all the energy used by the human race in 1970.

Chemical energy: The most important form of stored energy is the chemical potential energy of the fossil fuels. The energy in coal, for instance, was originally solar energy 300 or so million years ago. The huge mosses and ferns of the Paleozoic coal swamps died and fell into the mud. They were acted on by anaerobic bacteria that released much of their hydrogen as a gas. This in turn was driven off by the heat and pressure generated by the tons of sediment that covered them. In the process the carbohydrates were converted to the almost pure carbon of coal.

When the carbon atom is burned (oxidized), it releases the remaining stored energy in the reaction:

$$C + O_2 \rightarrow CO_2 + \text{Energy}$$

Some plant and animal life sank to the bottom of the great sea beds and went through a different chemical transformation under pressure and heat to form the "hydrocarbons," the complicated molecules of hydrogen and carbon characteristic of petroleum. Their stored energy is also released by burning.

In Table 1-3 we show the amounts of energy contained in the traditional measures of the fossil fuels; tons of coal, barrels of oil, and thousands of cubic feet of natural gas. For comparison, we also show the energy per pound of all of these. This latter comparison shows that energy per pound (the energy density) is greatest for natural gas, which is one of the reasons for the popularity of this fuel.

Chemical energy is used by man in other forms. Food energy is of this form. The energy stored in a battery is also chemical, stored in molecular rearrangements there and released when electrons are allowed to move through an external circuit. An important device of the future, the fuel cell, will also convert chemical energy to electrical energy; it will be described in a later chapter.

TABLE 1-3
Energy Content of Various Fuels

Fuel	Amount	Energy Equivalent (M Calories)	Energy per Pound (Calories)
Coal			
Soft coal (bituminous)	one ton	6.1	3,100
Hard coal (anthracite)	one ton	6.4	3,200
Oil, distillate (including deisel)	barrel	1.5	4,900
Gasoline	barrel	1.3	4,800
Natural Gas	1,000 ft^3	.26	5,000
Wood	1 cord[b]	5.3	1,250

[a] Million.

[b] One cord is a pile of wood 4 ft. long, 4 ft. high, and 8 ft. long.

Nuclear energy: A form of potential energy of growing importance is stored in the nucleus, the tiny, dense core of the atom. Nuclei are made up of the elementary particles, protons and neutrons. It is by rearranging these particles that nuclear energy is stored and released. The fission reaction and the fusion reaction are two important examples of this. In the fission reaction a heavy nucleus, such as uranium, is split into two lighter ones. In this process mass is converted into energy and it is this energy we obtain from the hot interior of a nuclear reactor. We describe this in more detail in Technical Appendix 6.

The fusion reaction involves very light nuclei. It is, as we have said, the source of the sun's energy. In a typical example, four hydrogen nuclei, by a complicated series of reactions, form a helium nucleus (two protons and two neutrons). Again, some of the mass has been converted to energy. It is a fusion reaction involving a rare form of hydrogen, deuterium, which scientists are now trying to master so that we can use the deuterium in the ocean as the fuel in a controlled fusion reaction. Our only duplication of the sun's process so far has been to perfect the so-called "hydrogen bomb," and that did little to help us in our quest for energy.

Geothermal energy: The earth's interior is molten rock, "magma" the geologists call it. There is, of course, a tremendous amount of geothermal energy in the earth. It is stored kinetic energy — heat energy — insulated by the solid, thin crust on which we live.

We are not sure how the energy got there; it may have been stored in the molten blob of original earth or it may have come from the impact of countless chunks of matter pulled to it by the earth's gravity in that formative period. We are fairly certain, however, that it is the radioactivity of some of the material in the earth which keeps it hot. There seems to be enough uranium, potassium, radium, and other naturally radioactive material in the earth's interior to produce the relatively small amount of heat needed to make up for that lost through the surface. In this sense, geothermal energy is nuclear energy.

Energy from the core leaks out in different ways. As we see in Figure 1-1, the largest amount, 32 B kw, is conducted through the crust in the same way that the heat from a hot pan of water is conducted through the sides of the pan. The insulation of the crust is not perfect. As we dig down into it, it gets hotter, 48°C for each mile we go in.

This temperature difference is not great enough to be of use as an energy source, although, in the future, we may pipe water down heating it to warm our houses. The leaks that are useful to us are in those regions where the magma is close to the surface. Volcanoes, geysers, and hot springs are evidence of this. The total power arriving at the surface by "convection " — that is, by the movement of hot rock, water, or steam — is estimated in Figure 1-1 as 300 M kw.

Of this total output, only a limited amount can be used. If available as hot water or steam, it can be used to heat buildings. Some 500 homes and offices in Klamath Falls, Oregon, are heated by hot water drawn from a hot spring running under the town. The only large-scale use of it in this country is in the Geysers Valley in California where dry steam — steam so hot there is no water in it — is piped to steam turbines and used to generate electricity. There are now generators there producing a total of 500,000 kw of electric power, about half of San Francisco's needs.

Geothermal energy, like nuclear energy, is an energy of the future. We will describe later on more of the details of its use, its potential, and its problems.

Tidal energy: The last of the big five, tidal energy, is probably the least in importance for man's use. It is relatively big, on a human scale, 3 B kw (see Figure 1-1), but is dispersed over all the oceans' shores.

The source of this energy is the kinetic energy stored in the rotation of the earth-moon system. Like geothermal energy, it is another example of the successful temporary storage of energy in the kinetic form. This energy is converted to the motion of the oceans through the gravitational attraction of the moon on their contents. The oceans' water is pulled toward the moon on the near side (and bulges in the other direction on the far side). The up and down (in and out) motion of the water can be used to turn a turbine. Tidal energy is finally dissipated by friction with the ocean shores, warming them imperceptibly.

Tidal generation of electricity is only practical where geologic peculiarities cause high tides. The first tidal dam and generator was built in the Rance estuary on France's Brittany coast, where tides rise and fall as much as 44 feet. It has a total generating capacity of about 300,000 kw.

There has also been some interest in building a tidal conversion facility at Passamaquoddy Bay on the far northern coast of Maine, but it does not yet appear commercially feasible. We cannot expect much contribution to our total supply of energy from the tides.

Summary

In this chapter we have tried to introduce you to the various forms of energy, the laws that govern its conversion from one form to another, and the patterns of energy flow that power the great natural engines of earth as well as man's puny manufactured ones.

Energy can be classified into two types, kinetic and potential energy. It is used in the kinetic form as heat, light (or, more generally, radiation), and motion. It is stored in the potential form.

Energy is used by conversion from potential to kinetic form or from one kinetic form to another. We have presented and discussed the two laws that govern all these conversions:

1. **Energy can be neither created nor destroyed.**
2. **In any conversion of energy from one form to another some of it becomes unavailable for further use.**

This second law, the "heat tax," will prove to be the most important to our understanding of the Energy Crisis.

In this chapter we define and give examples of the units in which we measure energy and power. We also define work, which is the word we commonly use for mechanical energy in man's use. The standard unit of work and energy in our presentation will be the *Calorie,* the energy required to raise the temperature of one kilogram of water one degree Celsius. The power unit will be the unit of electric power, the *kilowatt* (kw), whose definition we defer to Technical Appendix 3.

In the final section we look at the patterns of energy flow on earth. We see the dominance of the solar input and compare it with the nonsolar continuous sources of power, the tides and the molten interior of the earth. We end with the identification, from Figure 1-1, of the five primary forms of energy on earth: the three kinetic forms, *solar, geothermal,* and *tidal,* and the two potential forms, the chemical energy of the *fossil fuels* and the *nuclear energy* stored in the atom's core.

The rest of our story will revolve around these five forms and what happens when they are mined, tapped, or trapped and then burned or otherwise turned to our uses. The next question is, however, "How much is there?" We shall answer that in the next chapter.

CHAPTER 2

The Energy Stockpiles

The Energy Stockpiles

In the preceding chapter we describe the five major energy flows to and on earth. Three of these are kinetic energy, the constantly radiated energy from the sun and the energy stored in the rotation of the Earth-Moon system and in the Earth's molten interior. The other two major flows are from potential energy, stored in the atoms of the fossil fuels and in the nuclei of uranium or similar heavy elements.

More important than the kinetic-potential distinction is the distinction between continuous and depletable resources. From our myopic view of the sweep of time, solar and tidal energy can provide a continuous flow of power, while chemical and nuclear potential energy are drawn from a limited stockpile. Geothermal energy falls in between. Although the ultimate source of this energy is so large that it is for all practical purposes infinite, the actual geothermal reservoirs are not infinite and can be exhausted by drawing the heat energy out of them faster than it comes in from below. For the purposes of this chapter we will consider it a depletable resource.

Figure 1-1 gave the big picture of these energy flows. A more human-sized catalog is provided by Table 2-1 in which the various sources of power (continuous energy sources) are presented in terms of power per acre. In this table we show not only the big one, solar power, but the sources of "secondhand" solar power, the winds, photosynthesis, and the energy of running water. For comparison we also show the United States power consumption in 1973 (the total energy consumption in kilowatt hours divided by the number of hours in a year) averaged over the 2,310 million acres of the 48 contiguous states.

Table 2-1 shows us that man has gone big time. His consumption of power per acre is larger than all but the total of the winds and the direct solar energy. If we harnessed all the running water in this country, it could only provide a tenth of our needed power; geothermal power, in this reckoning, could provide one-fifth. Most surprising, perhaps, is the insufficiency of photosynthesis. If we burned all the biological growth our land produced in one year, we would obtain one-third the power we now consume.

TABLE 2-1
Power Per Acre on Continuous U.S.

Source	Kilowatts per acre
Sunlight at Top of Clouds (day/night average)	1,420.
Sunlight Absorbed at Ground Level (averaged)	810.
All the Winds	2.8
All the Tides	0.02
Natural Geothermal (steam and hot water)	0.25
All Photosynthesis	0.32
All Hydropower	0.12
1973 U.S. Energy Consumption, average per acre	1.1

Source: Briefings before the Task Force on Energy of the Subcommittee on Science, Research, and Development, Committee on Science and Astronautics, U.S. House of Representatives, 92nd Congress, Serial Q, March 1972, pg. 79.

The message of Table 2-1 is "look to the sun," and we will, in Chapter 7 of this volume, consider ways of using this enormous energy flow to meet our growing needs. Now, however, we turn away from these energy flows to the stockpiles of chemical and nuclear energy and try to gauge their size.

The Fossil Fuels

The stockpiles of the fossil fuels are difficult to measure. They are in fact part of the small planet we live on and must be discovered and extracted before we really know how much is there. Our numbers will, therefore, have built-in uncertainty.

In order to give some idea of the degree of uncertainty, we will present our data in the categories indicated on the graph illustration of Figure 2-1. The resource estimates will have two distinctions applied to them, "identified" and "undiscovered," "recoverable" and "submarginal." The first distinction is an obvious one. In the distinction between recoverable and submarginal resources, both price and technological "know-how" must be taken into account. In the case of coal, for instance, it is not presently economical to mine high grade coal from seams thinner than 42 inches. In the case of oil shale, all of this resource was considered submarginal until the increase in oil prices in 1973-1974 made it appear economically feasible to begin to extract this oil from rock. We will present, in the text and illustrations which follow, the estimates of resources in these various categories relying on data from the U.S. Geological Survey.[1]

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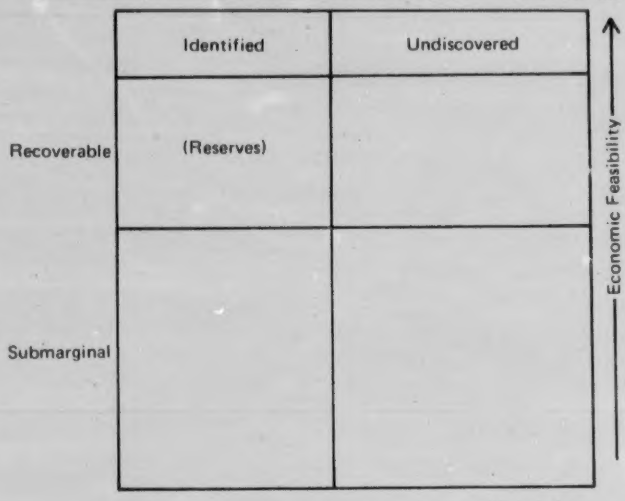
[1] "Energy Resources of the United States." P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan. **Geological Survey Circular 650.** Washington, D.C. 1972.

FIGURE 2-1
Presentation of Resource Data (Area of rectangles are proportional to resource amount)



Recovery: It is, unfortunately, not enough to present estimates for the total amounts of resources. What we are really interested in is how much of the resource we can mine or pump for our use. We need, therefore, to know more about the actual extraction process. In the traditional method of underground coal mining, for instance, the mine roofs are supported by pillars of coal and about 50 percent of the coal is left in the mine for this purpose. In surface (strip) mining 75-80 percent of the coal is recovered.

The situation with oil is even worse. With present techniques, only 31 percent of the oil is extracted; two barrels are left in the ground for every one recovered. Techniques are under development to improve this recovery percentage. In one an underground oil pool is set on fire along one side with the hope that the fire, advancing across the pool, will heat the remaining oil, increase its pressure, and drive more of it up the wells. In others steam and water under pressure are used to force more oil up the wells and detergents are added to make thick oil flow more easily.

Natural gas, being highly mobile, is more easily recoverable than oil. We are able to extract about 80 percent of the total discovered amount of this fuel.

These recovery percentages are used in the resource summaries which follow to compute the "recoverable" amount of a fuel (50 percent in the case of coal, for instance), while the nonrecoverable amount is included in the "submarginal" categories. Let us now briefly consider each of the fossil fuels.

Coal: Coal is the most plentiful of these fuels. We call it fossil because it is made up of the remains of once-living plants. It dates from the Paleozoic era, 300-500 million years ago. The earth at that time was warm and wet and the atmosphere had a higher carbon dioxide content than it does now. In this "greenhouse" environment vegetation flourished. The carbon we burn as coal today was taken from the air's carbon dioxide by the strange jungles of giant mosses and ferns which covered much of the earth in that era.

These plants died, fell into the mud and water of those swampy jungles, were preserved from decay (which would have released their energy) by the water covering them, and gradually built up, layer after layer, into a thick deposit. These layers were covered by tons of earth washed down from the mountains. Under that pressure, and the resulting high temperatures, the volatile gases (hydrogen and oxygen and their compounds) and the water were driven off resulting in almost pure carbon. Coal is as much as 80 percent carbon in contrast to the 50 percent or so in living material. Since the energy resides largely with the carbon (and is released by combination with oxygen in burning), coal has a higher energy density than living material. Burning a pound of wood, for instance, releases only about 1,250 Calories of energy, while one pound of high grade coal releases 3,100 Calories when burned (see Table 1-3).

Knowing how coal was formed helps greatly in finding it. It is possible from outcroppings, drillings, etc. to estimate fairly accurately how much is in a given seam. The U.S. Geological Survey estimates of this resource are given in Figure 2-2. Figure 2-3 shows where it is and how it can be mined.

The "reserves," the coal that has been identified and is economically recoverable, amount to 390 billion (B) tons. For comparison, about 600 million (M) tons of coal were mined in 1974. In addition to these reserves, another 1,200 B tons of coal that is not at present economically feasible to extract has been identified. This "submarginal-identified" resource includes the other 50 percent of the coal left in the ground when the reserves are extracted. The Geological Survey warns us that the reserves are known to an accuracy of only about 20-50 percent while the undiscovered submarginal resources might be in error by as much as a factor of five or 10.

We summarize the resource picture in terms of Calories as well as B tons in Table 2-2. The question of what totals to display returns to trouble us. The "reserves" seriously underestimate the potential fuel; oil, for instance, is being discovered every day and added to the reserve category. The sum of all the four blocks of figures like 2-2 are misleading in the other direction, much of the submarginal category will never be mined or pumped or perhaps even discovered. The choice we have made is shown in Table 2-2. We show the "reserves" which are the lower limit of the fuel available, and then the total of the "recoverable" category, which is effectively an upper limit consistent with present technology and economics. The third category, "total resources," does not provide a realistic estimate of potential; we include it to show that even this category, while large, is still finite.

FIGURE 2-2
U.S. Coal Resources (in billions of tons)

	Identified resources	Undiscovered resources	
		0-3,000 ft overburden	(c)
Recoverable	200(a) 190(b)		0
Submarginal	1,200	1,300	340

Source: "Energy Resources of the U.S.," P. K. Theobald, S. P. Schweinfurth, and D. C. Duncan, **Geological Survey Circular 650**, Washington, D.C. 1972.

(a) Recoverable coal in beds 42 inches or more in thickness for bituminous coal and anthracite and 10 feet or more in thickness for subbituminous coal and lignite.

(b) Additional coal recoverable in beds 20-42 inches in thickness for bituminous coal and anthracite and 3-5 feet in thickness for subbituminous coal and lignite.

(c) 3000-6000 ft overburden

The coal resources, in contrast to oil resources, as we shall see, are pretty well known. No further recoverable resources of coal are expected to be discovered. The 390 B tons of reserves are, however, already large compared to other fuels and the improvement of underground coal mining to bring its recovery factor above 50 percent will shift some of the 1,200 B tons of submarginal resources into the reserve category.

Oil: Oil is formed by a process similar to the one that produces coal. Instead of being the fossil remains of plant life, however, oil seems to have been formed from sea animals as well as plant remains which sank to the bottom of the great seas that covered the earth in earlier geologic periods. Oil is younger than coal, only a few tens of million years old instead of hundreds of millions. It was also formed by pressure and the resulting heat. Instead of the simple carbon atoms which form the crystalline solid of coal, petroleum consists of a great variety of complicated hydrocarbon molecules, large molecules of carbon and hydrogen. The petroleum products themselves range from the thick heavy tars and asphalts (the largest molecules), through the oils, gasoline, and kerosene, to the natural gases like methane, which is a carbon atom plus four hydrogen atoms. The various lighter components of petroleum are formed from the heavier ones by "*cracking*"; they are broken down by the heat. It is this same process which is used in a refinery to produce gasoline (one of the lighter molecules) and the other products, kerosene, diesel oil, the fuel oils, etc.

We can again, from the rough knowledge of its formation, guess where oil will be found. The areas to explore are the sedimentary basins which were once oceans. Oil, however, is not as predictable as coal, and the same kind of rock which will be loaded with oil in Iran will be dry

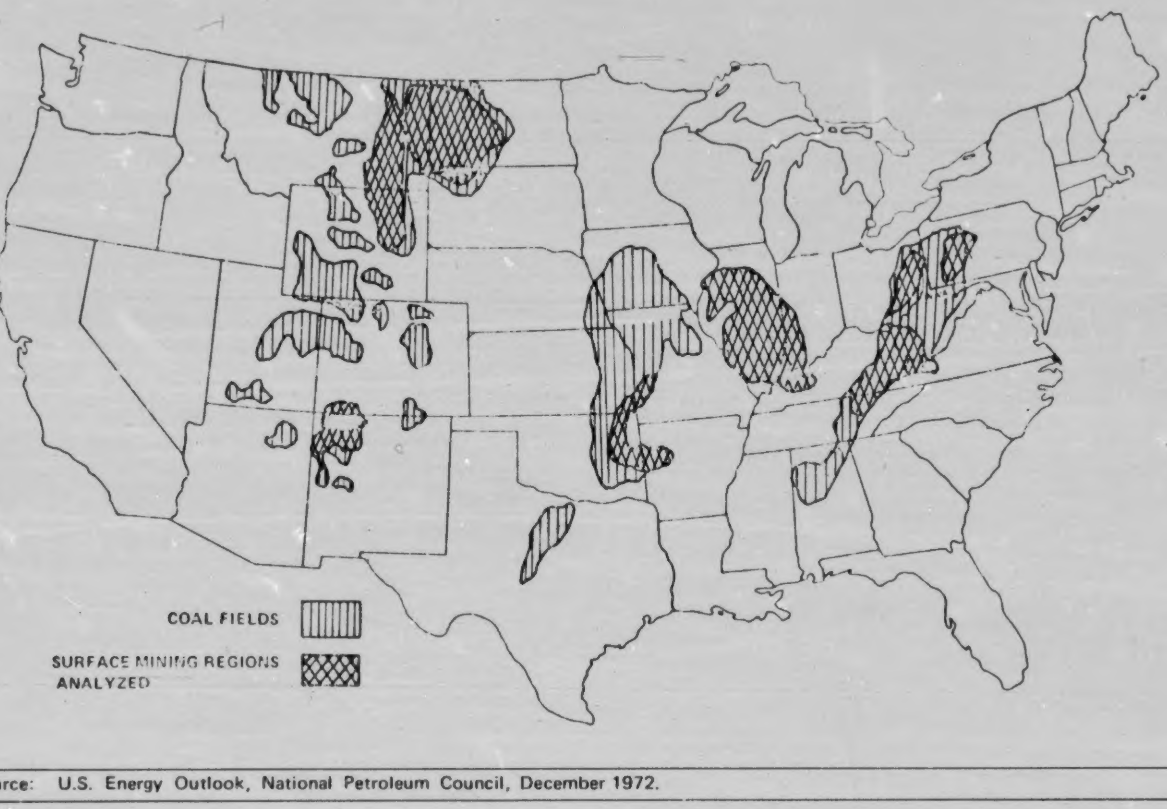
TABLE 2-2
U.S. Coal Resources

Category	Amount (B tons[a])	(Q Calories[a])
Reserves[b]	390	2,380
Thick Seams[c]	200	1,220
Intermediate Seams[d]	190	1,160
Ultimately Recoverable	no additional discovery	
Total Resource	**3,200**	**19,500**

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650**, Washington, D.C., 1972.

[a] B (billion, 10^9) tons; Q (quadrillion, 10^{15}) Calories.
[b] A recovery of 50 percent is assumed.
[c] Greater than 42" for high grade coal and 10' for lower grade coal.
[d] 28" to 42" for high grade and 5' to 10' for low grade coal.

FIGURE 2-3
Coal Fields in the United States



Source: U.S. Energy Outlook, National Petroleum Council, December 1972.

in Australia. Even in the well-explored United States it is estimated that more than half the oil is yet to be discovered.

The U.S. Geological Survey estimates of total United States oil resources are shown in Figure 2-4. The reserves are again relatively small, 52 billion barrels (B bbls) of oil which can be recovered (at a 35 percent rate of recovery) from identified oil fields. The map of Figure 2-5 shows the United States oil fields.

FIGURE 2-4
U.S. Oil Resources (in billions of barrels)

	Identified Resources	Undiscovered Resources
Recoverable	52	450
Submarginal	290	2,100

Source: "Energy Resources of the U.S.," P. K. Theobald, S. P. Schweinfurth, and D. C. Duncan, **Geological Survey Circular 650**, Washington, D.C. 1972.

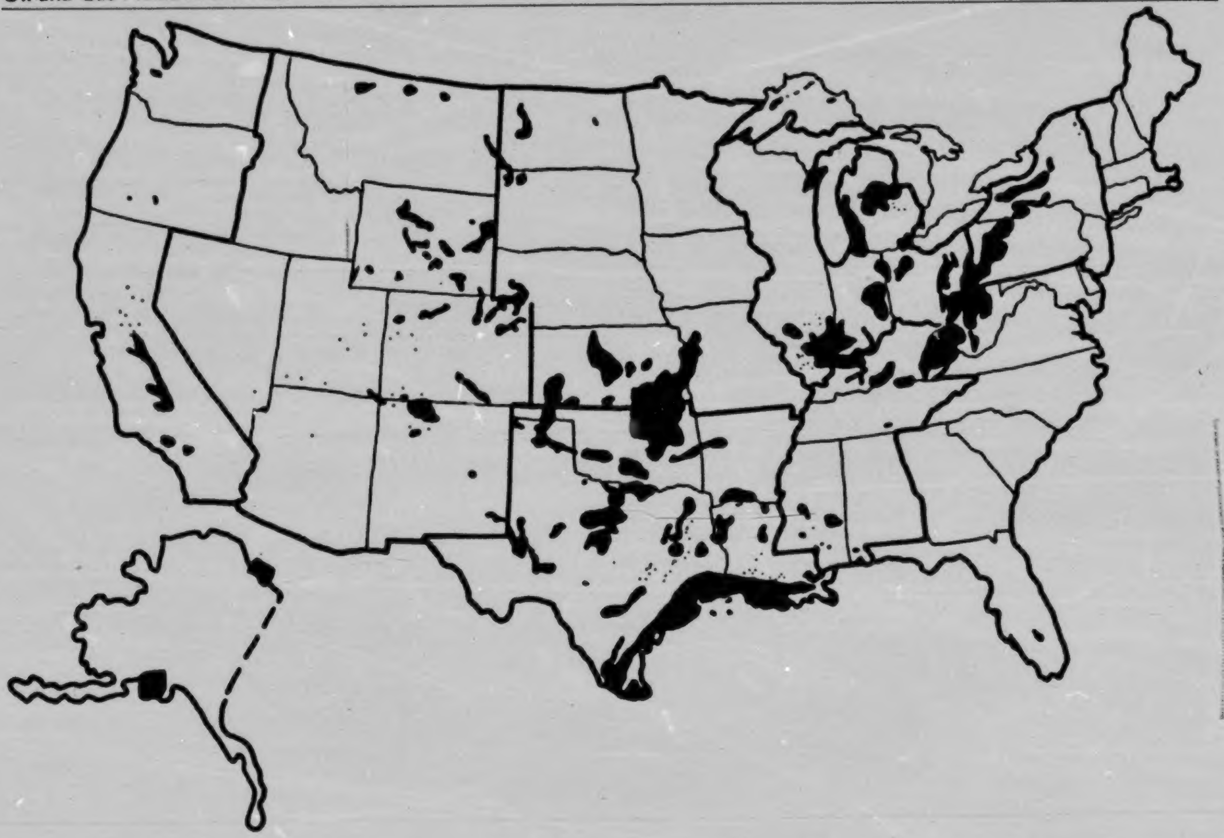
Even this oil will not be easy to extract; of the 52 B bbls of reserves, 11 B bbls are in Alaska, 6 are offshore from the United States and Alaska, and the remaining 35 B bbls are on the United States land area. Of this latter, much is accessible only to keep drilling.

Identified submarginal oil, 290 B bbls, includes all the oil left in the ground from past extraction and that which will be left by present techniques when the reserves are extracted.

As we did in Table 2-2 for coal, in Table 2-3 we show the total B bbls and Calories for oil of the three resource categories. The 502 B bbls is thus a fairly realistic upper limit of the total amount of oil we can count on. It will take considerable improvement in technology to enable us to get more of the existing oil out of the ground and thus move some of the 290 B bbls of identified-submarginal and 2,100 B bbls of undiscovered-submarginal oil up into the "reserve" category.

Natural gas: Natural gas is formed by the same processes which form oil. It consists primarily of methane, as we have said, but contains as well smaller

FIGURE 2-5
Oil and Gas Fields in the U.S.



Source: Department of the Interior, U.S. Energy Fact Sheets 1971, February 1973.

amounts of other similar but more complex hydrocarbons. Some of these are liquid at room temperature but become a gas at slightly higher temperatures. These "Natural Gas Liquids," like propane and butane, are NGLs.

Natural gas originates with oil and in fact often helps provide the pressure which drives the oil from the well. Such gas is called "associated" gas. Since it is so much more mobile, however, gas can move through cracked rock or sandstone and collect in a separate deposit, referred to, not unreasonably, as "non-associated" gas.

Because of its mobility and its discovery with and without oil, it is extremely difficult to estimate the size of undiscovered resources. One can determine the average amount of gas formed per barrel of oil and use this to estimate the "associated" gas in oil resources. The amount of "non-associated" gas discovered per foot of drilled well fluctuates wildly from year to year and provides no reasonable statistics.

With this admission of uncertainty, we show, in Figure 2-6, the natural gas resources (in trillions of cubic feet, TCF). The 170 TCF of identified but submarginal natural gas includes that 20 percent left when the identified, recoverable gas (reserves) is extracted, plus other identified quantities whose recovery is not presently projectable.

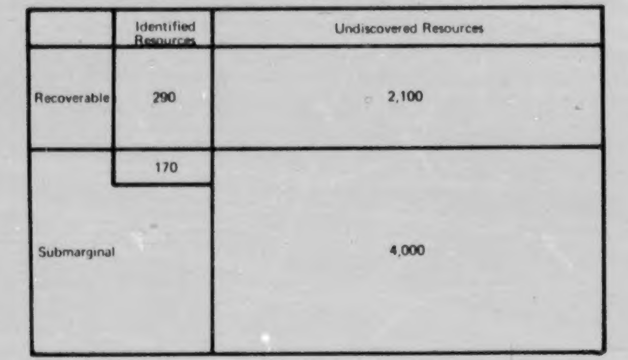
TABLE 2-3
U.S. Oil Resources

Category	Amount (B bbls(a))		(Q Calories(a))	
Reserves(b)		52		78
U.S. Land Area	35		53	
Offshore	6		9	
Alaska	11		16	
Ultimately Recoverable(b)		502		753
Total Resource		**2,892**		**4,340**

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650**, Washington, D.C., 1972.

(a) B bbls (billion, 10^9 barrels); Q (quadrillion, 10^{15}) Calories.
(b) A recovery factor of 35 percent is assumed.

FIGURE 2-6
U.S. Natural Gas Resources (in trillions of cubic feet)



Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the U.S.," **Geological Survey Circular 650**, Washington, D.C., 1972.

Of the 290 TCF of reserves, 30 TCF are in Alaska, 40 TCF offshore, and the remaining 220 TCF on the United States land area. As was the case with oil, those 2,560 TCF of ultimately recoverable gas will be increasingly more difficult to find and extract. It is expected that two-thirds of this amount will be in operationally difficult areas, at deeper than 15,000 feet, for instance, or offshore, or in Alaska. This gas will therefore be much more expensive to produce.

Estimates of the total gas resource vary by a factor of three, with the highest total almost double the one we show in Figure 2-6. For consistency with this chapter, however, we will use the U.S. Geological Survey data throughout. In Table 2-4 we provide a summary of the total number of TCFs and Calories of natural gas in the three resource categories.

Oil shale: A new entry on the list of resources is oil shale. Some of the petroleum formed at the bottom of the sea beds did not escape as a liquid or gas but was instead bound into the clay sediment itself which, after eons of pressure and heat, became a *flaky, soft* rock called shale. The amount of petroleum bound in these rocks can be quite high. Some of the shale in the deposits in pre-war Estonia average 1½ to 2 barrels of oil (63 to 84 gallons) per ton of rock and can be burned as it is. Most of the shale, however, assays at only a few gallons per ton.

The most significant United States oil shale deposits are in the Colorado, Wyoming, Utah area shown on the map of Figure 2-7. The richer shales shown by the darker shading have oil content of at least 25 gallons per ton and these will be the first shales mined. The various resource categories are shown in Figure 2-8.

The recovery of oil from oil shale is just beginning to be economically feasible. The rock must be mined, crushed, and then heated to drive out the oil. At the time

TABLE 2-4
U.S. Natural Gas Resources

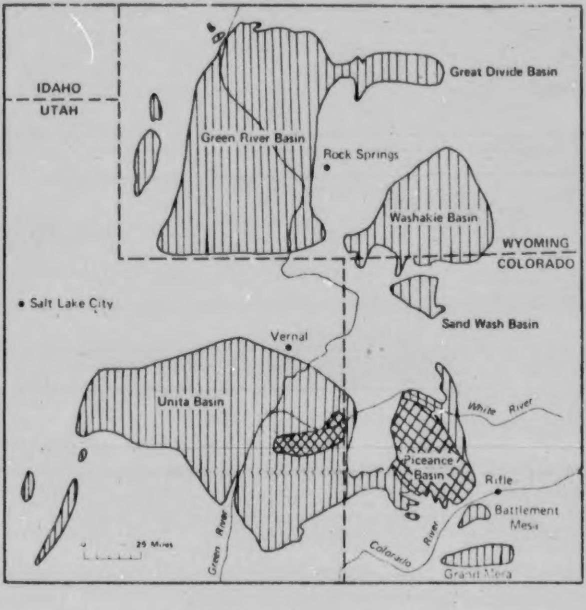
Category	Amount (TCF(a))		(Q Calories(a))	
Reserves(b)		290		75
U.S. Land Area	220		57	
Offshore	40		10	
Alaska	30		8	
Ultimately Recoverable		2,560		621
Total Resource		**6,560**		**1,710**

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650**, Washington, D.C., 1972.

(a) Trillion (10^{12}) cubic feet; Q (quadrillion, 10^{15})
(b) Recovery factor of 80 percent is assumed.

of preparation of Figure 2-8, the expected cost of recovery of this oil, about $6 per barrel, was too high to allow it to compete with cheap Mideastern and South American oil. The tremendous price increases in 1973-1974 allow us to change the designation of the 160-600 B bbls shown as "paramarginal" in the original U.S. Geological Survey presentation to "identified recoverable" in our version. We should still caution, however, that large-scale processing of oil shale is only just beginning and it is not at all certain that we should really consider oil from shale as a "reserve." We continue in this cautious interpretation in Table 2-5 and include under "ultimately recoverable" only the 600 plus 850 B bbls from the "identified" and the "extension of known resources" categories of Figure 2-8.

FIGURE 2-7
Major Oil Shale Resources



▥ Area underlain by the Green River Formation

▨ Approximate extent of selected minable seam in the Mahogany Zone (at least 30 feet thick and averaging at least 30 gal./ton).

Source: U.S. Energy Outlook, National Petroleum Council, December 1972.

FIGURE 2-8
U.S. Oil Shale Resources (in billions of barrels)

	Identified Resources	Undiscovered Resources	
		Extension of known resources	Undis. & Unappraised
Recoverable	0	0	0
Paramarginal	160 - 600(a)	850	500
Submarginal	1,600	2,500	20,000

(a) Oil content greater than 25 gallons barrels per ton.

Source: "Energy Resources of the U.S.," P. K. Theobald, S. P. Schweinfurth, and D. C. Duncan, **Geological Survey Circular 650,** Washington, D.C. 1972.

Tar sands: There is a fourth, rather small potential source of oil similar to the shales. In this case the oil, rather than impregnating shale rock, has been formed in sand and binds this material together. It must be processed in a manner similar to shale, mined and then heated. There is essentially no United States experience with tar sand (although the Canadians are mining tar sands in Alberta), so the only category which it can be put into at present is that of total resource. The 18-28 B bbls resource shown in Table 2-6 is an estimate of the content of some known deposits in Utah.

Nuclear Fuels

The nuclear reactor is a newcomer in the energy scene. Only in the past three or four years, in fact, have these plants begun to produce more electricity than they consumed in their manufacture and in the processing of nuclear fuel.

TABLE 2-5
U.S. Oil Shale Resources

Category	Amount (B bbls(a))	Amount (Q Calories(a))
Reserves(b)	160-600	240-900
Ultimately Recoverable	1,010-1,450	1,520-2,180
Total Resource(c)	5,110-5,550	7,670-8,330

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650,** Washington, D.C., 1972.

(a) B bbls (billion, 10^9) barrels); Q (quadrillion, 10^{15}) Calories.
(b) Oil content greater than 25 gallons per ton and deposits greater than 10 feet thick. One hundred percent recovery assumed for lack of relevant experimental data.
(c) Includes only "identified recoverable" and "extension of known resources" from Figure 1-6.

TABLE 2-6
U.S. Tar Sands Resources

Category	Amount (B bbls(a))	Amount (Q Calories(a))
Total Resource(b)	18-28	27-42

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650,** Washington, D.C., 1972.

(a) B bbls (billion, 10^9 barrels); Q (quadrillion, 10^{15}) Calories.
(b) No estimate of recovery factor.

There is much of interest to say about nuclear reactors, about how they work and their advantages and disadvantages compared with other sources of power. We will enter this discussion in a later chapter. In this one, we will limit ourselves to an estimate of the size of the fuel stockpile and discuss the process of using this fuel only where it is essential to understanding that estimate.

Uranium: The most important nuclear fuel is uranium, one of the heaviest of the elements. It is a radioactive element and, in fact, the uranium prospectors, so much in evidence in the 1950s, used detectors of radioactivity, "Geiger counters," to look for it.

Uranium is a rare mineral. On the average it occurs in a ratio of 2 parts per million (ppm) in the earth's crust. It occurs in greater concentrations in certain rocks and ores; this concentration ranges from 4 ppm in granite, to 70 ppm in the Chattanooga shales, to 2,000-3,000 ppm in the uranium ores which are mined commercially.

If the "breeder reactors," which we will describe in the chapter on new energy technology, come into being, some of the dilute uranium ores, even the Chattanooga shales and granite, could be used as fuel. At present, however, we will explore the size of the resource in terms of the richer ores.

Uranium is mined and refined to a uranium oxide, U_3O_8. The resources are traditionally expressed in terms of tons of U_3O_8 and we will follow this practice. In assigning the amounts of identified ore to the various categories, the price for the recovery of the U_3O_8 is the dominant factor. In 1970 the ore was produced for $8 per pound or less and that price is chosen for the cut-off between the recoverable and the submarginal categories. In this latter category only uranium that can be produced for less than $15 per pound is listed. As the price of electricity increases, more expensive ores can be added to the resource estimate. This will be especially true if the "breeder reactor" enters the picture, for then the cost of the ore will be only a small part of the total cost of electricity.

Figure 2-9 shows the U.S. Geological Survey estimate of uranium resources, and Figure 2-10 gives the location of the most important deposits. To the recoverable and submarginal categories already discussed, we add a third category, "by-product." There are two existing processes that produce uranium as a by-product. One of these is copper mining and the other the mining and refining of phosphate rock in the manufacture of fertilizer. It is estimated that at least 1,000 tons per year of U_3O_8 at under $10 per pound could be obtained from the copper ores and that similar amounts could be obtained from the phosphate rock. It must be pointed out that these prices for the U_3O_8 assume that the recovery of uranium is part of the mining-refining process for these ores. If the uranium is thrown away, as it is now, it is removed from the by-product category, and its cost of recovery increases.

The summary, Table 2-7, is presented in terms of price as this is the most important determinant of the

FIGURE 2-9

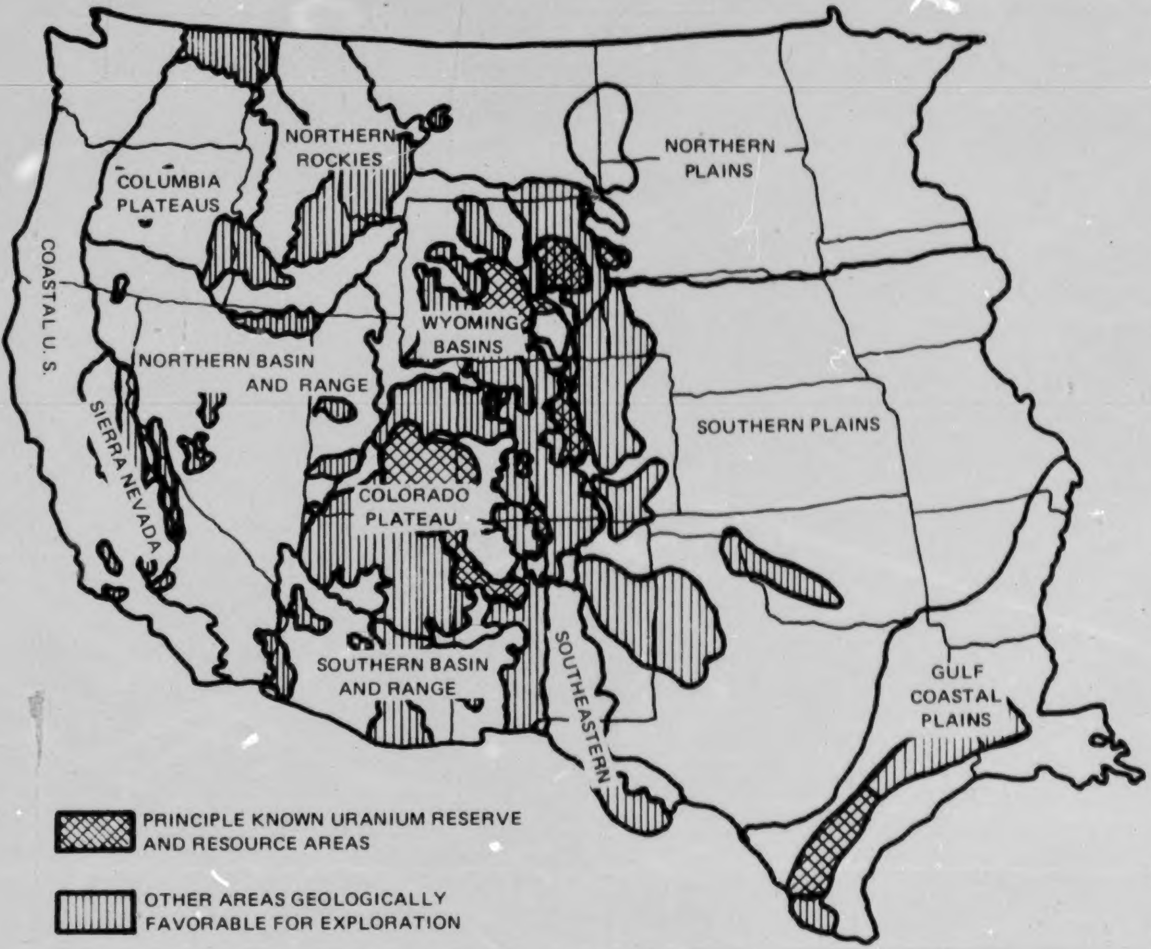
U.S. Uranium Resources (in thousands of tons)

	Identified	Undiscovered (In known districts)	(In unknown districts)	
Recoverable(a)	250	500	250	
Submarginal(b)	200	400		
By Product(b)	1,000			

recoverable or submarginal classification. The conversion of tons of U_3O_8 to Calories, however, cannot be made without some reference to what takes place in the reactor. For the present we will base our results on two pieces of information (from the Atomic Energy Commission). A 1,000 megawatt (million watt, Mw) conventional reactor plant operating at 75 percent capacity uses about 130 tons of U_3O_8 per year. During that year it will generate 6.6 B kw-hrs of electricity. Since, at the present time, electric energy is the only output of the reactor, we will use for our conversion 130 tons of U_3O_8 as the equivalent of 6.6 B kw-hrs (5.7 T Calories) of energy or 44 B Calories per ton. The energy equivalents of the various classes of uranium resources shown in Table 2-7 use this conversion.

What is surprising is the relatively small size of the uranium resource. It must be remembered, however, that this computation of Calories is based on the generation of electricity in the present, not very efficient, "light water reactor," whereas the other fuels are converted to Calories at full value. The price factor also enters in. We have included only the total resource available at less than $15 per pound. If we were to move the scale up to $30 per pound, we could add another 1,300,000 tons to the total resource. Even with this explanation, Table 2-7 reminds us that uranium is also a finite resource. It has, however, a potential of extension the others do not have. The present reactors use a rare form of uranium, the isotope U^{235}. ("Isotopes" and the meaning of numbers like 235 are explained in Appendix 6.) U^{235}

FIGURE 2-10
Uranium Resources Western United States


NORTHERN ROCKIES
COLUMBIA PLATEAUS
NORTHERN PLAINS
COASTAL U. S.
WYOMING BASINS
NORTHERN BASIN AND RANGE
SIERRA NEVADA
SOUTHERN PLAINS
COLORADO PLATEAU
SOUTHERN BASIN AND RANGE
SOUTHEASTERN
GULF COASTAL PLAINS
▩ PRINCIPLE KNOWN URANIUM RESERVE AND RESOURCE AREAS
▥ OTHER AREAS GEOLOGICALLY FAVORABLE FOR EXPLORATION

Source: U.S. Energy Outlook, National Petroleum Council, December 1972.

is present as less than 1 percent of the total amount of uranium. The rest of the uranium, the isotope U^{238}, is not used. If the breeder reactor works and is judged safe enough to use, it can convert the common U^{238} to fuel as well and the resources tabulated in Table 2-7 will be multiplied by perhaps a factor of 50. The uranium resources then begin to rival coal in energy content.

Thorium: The other naturally occurring nuclear fuel is thorium. This is also a rare material; a metal-like uranium that is also radioactive. It is more abundant than uranium, averaging about 12 ppm in the earth's crust as against uranium's 2 ppm.

Thorium is used only in one existing reactor, the high temperature gas reactor (HTGR) at Peach Bottom, Pennsylvania, where it makes up only 10 percent of the fuel load. Another HTGR is under construction at Fort St. Vrain, Colorado. The HTGR is a breeder reactor and the thorium is converted into a uranium isotope, U^{233}. We describe these reactors along with the others in Technical Appendix 6. For now it is sufficient to say that thorium is a submarginal fuel which waits on further technological development for full use.

A large supply of thorium awaits utilization. In the Northwest, at Lemki Pass in Idaho and Montana, some 47,000 tons of thorium oxide ore have been identified and another 335,000 tons is inferred there. There are also deposits in the Southeastern United States.

We show, in Table 2-8, the most recent AEC estimates of thorium ore available at less than $10 per pound. These are minimal estimates since very little exploration for thorium has actually taken place. We do not convert the tons of ThO_2 to Calories in this table, as the conversion process is still too new to give us a reliable guide. Since the energy ultimately available from a pound of thorium is about the same as is available from a pound of uranium, we see by reference to Table 2-7 for uranium that there is also much energy waiting for us in the thorium deposits.

The Other Sources

We have now summarized the extent of our resources of fossil fuels and have also looked at the nuclear fuels we will be counting on more and more heavily in the next several decades. We will finish up this tabulation by looking briefly at three other sources of energy of varying importance. These are tidal energy, which is not presently used in the United States although it is used elsewhere, geothermal energy, which is beginning to assume some importance here and globally as well, and the oldest one of them all, the energy of falling water.

Energy from the tides: As we can deduce from either Figure 1-1 or Table 2-1, we cannot expect much help from the tides. The amount of energy in them is fairly small. The practical restrictions are even greater. There must be a tidal change of 15 feet or so to make such an operation worth considering; there must be a considerable flow of water, and so on. The only serious study of such a project in the United States has focused on the Passamaquoddy Bay between Maine and Canada. The studies have not so far showed a reasonable commercial feasibility.

Geothermal energy: The steam created by conduction from the earth's molten interior is an old, new source. Steam from the Lardello, Italy, geothermal field has been turning electric generators since 1904. We did not begin to use this free energy in this country, however, until 1960 and even now our one operating field, California's The Geysers, has a total capacity of 500 Mw, only about 0.1 percent of the nation's total generating capacity. This capacity, however, is now the largest of any of the world's geothermal generating systems.

From such meager experience with geothermal energy, resource estimates are very uncertain. The U.S. Geological Survey estimates are shown in Figure 2-11. (We consider geothermal energy here as a finite resource for reasons we have already mentioned — the available energy can be used up faster than the heat conduction can replace it.) A map showing the clustering of these resources in the far West is shown as Figure 2-12.

The resource estimate shown in Figure 2-11 differs from the others in that it is given directly in Calories. This is appropriate because this resource is already in the

TABLE 2-7
U.S. Uranium Resources

Category	Amount (Millions of tons)	(Q Calories[a])
Reserves (less than $8 per pound)	250	11
Ultimately Recoverable (less than $8 per pound)	1,000	44
By-product (less than $10 per pound)	1,000	44
Total Resource (less than $15 per pound)	2,600	114

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650**, Washington, D.C., 1972.

TABLE 2-8
U.S. Thorium Resources (ThO_2)

Category		Amount (Thousands of tons)
Reserves (identified and less than $10 per pound)		65
Lemki Pass	47	
S.E. United States	18	
Ultimately Recoverable (identified and inferred at less than $10 per pound)		400
Lemki Pass	382	
S.E. United States (no additional discovery as yet)	18	

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650**, Washington, D.C., 1972.

form of heat energy. In arriving at the 2,250 Q Calories, the total amount of heat energy available in steam from the Geysers and other known areas (excluding those in our National Parks) is reduced by the 15 percent efficiency with which this steam is produced. There are about 2,000 Q Calories of measured resource and 3,000 Q Calories inferred in the Geysers alone, and another 10,000 Q Calories inferred or measured elsewhere. Thus, from this total of 15,000 Q Calories, we can only expect to extract 2,250 Q Calories.

FIGURE 2-11
U.S. Geothermal Resources (in Q [10^{15}] Calories)

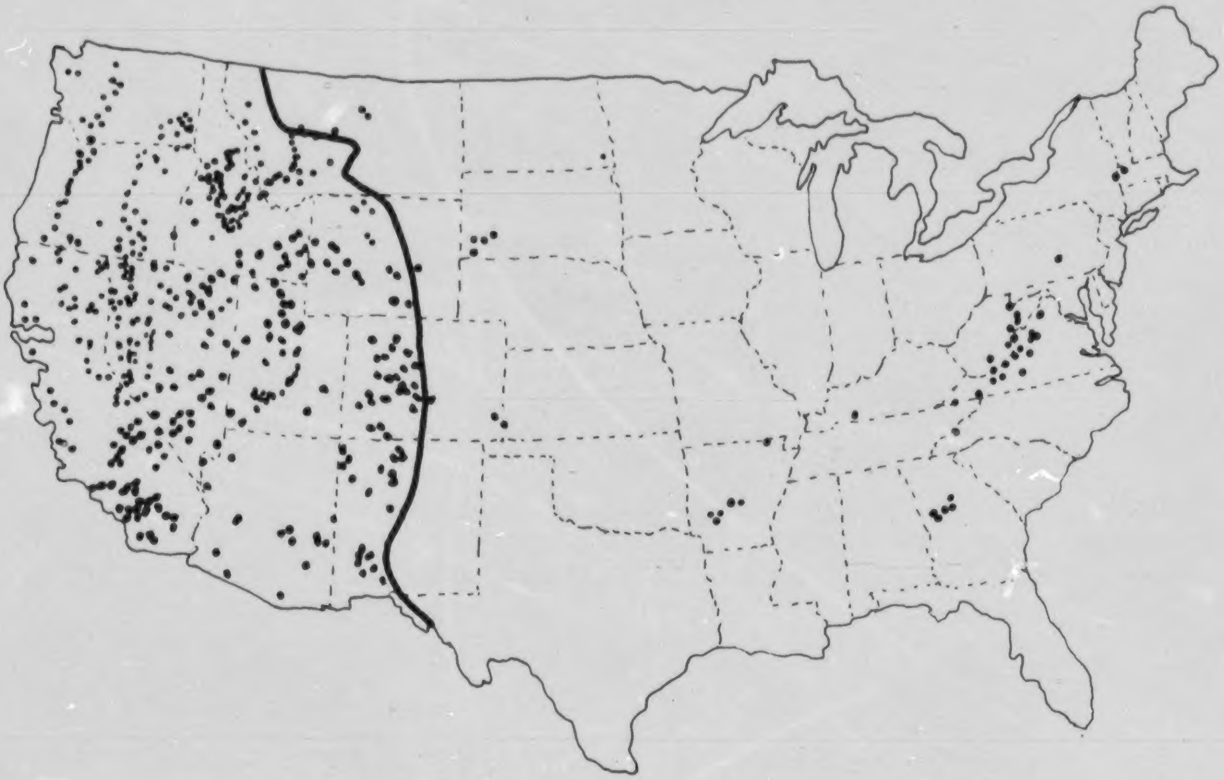
	Identified Resource	Undiscovered Resources
Recoverable	2,250	
Sub-Marginal	> 10,000,000	

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the U.S.," **Geological Survey Circular 650**, Washington, D.C., 1972.

The much larger submarginal figure of greater than 10,000,000 Q Calories is of a different sort altogether. The Geysers turbines use "dry steam," steam that is so hot there is no water mixed with it, and very little in the way of other impurities. Such steam can be piped directly to the turbines with only some simple screening to remove abrasive particles. The recoverable resources estimate is also restricted to dry steam fields. If we also include steam that is not so hot, hot water, and even hot rocks at a reasonable depth of 10 kilometers (about 6 miles), we get the much larger submarginal estimate. To use these forms of geothermal energy will take new technology. We will, therefore, look again at this resource in Chapter 7.

Water power: The oldest of the sources of energy we have been considering here is water power. Water wheels were put into use by the Romans at about the

FIGURE 2-12
Location of Geothermal Resources in the U.S.



Data from "Project Independence Report," Federal Energy Administration, November 1974.
- Areas of Promise

time of Christ and were, with wind, a source of power long before the steam engine.

Table 2-1 warns us that it is not a source with large potential. Except for a few grain mills, in this country we use it exclusively for the generation of electricity, to which it contributes about 15 percent of the total. From stream-flow data it is found that the production of this 15 percent already uses about a third of the total potential energy from flowing water available to us. Much of the remaining potential is protected by legislation such as the Wild and Scenic Rivers Act. The Federal Power Commission predicts that the 51,600 Mw of 1970 hydropower generating capacity will increase to 82,000 Mw by 1990. There is not much potential for increase beyond that.

United States Energy Stockpiles

Table 2-9 summarizes the resource information we have just discussed; the same data is presented graphically in Figure 2-13. These presentations emphasize again the dominance of coal in the resource picture; it is 30 times as abundant in the reserves category as oil or natural gas. Oil shale, in fact, is the next largest reserve, but the practical availability of that fuel is yet to be tested. The actual amount of energy from this source we will extract and consume will, in all likelihood, be considerably smaller than the amount we show as a reserve in Table 2-9.

World Energy Supplies

One of the most important lessons of the science of ecology is that "everything is connected to everything else." We are beginning to learn that lesson on a human and global basis where energy is concerned. We learned the obvious lesson of our dependence on the oil-rich countries of South America and the Mideast during the embargo the Arab countries placed on oil shipments in 1973-1974. We will see subtler instances of it as energy shortages in other countries cause political, social, and economic changes which affect us. It is necessary, therefore, even in a Source Book intended for a home audience, to look at least briefly at the energy resources of the world. We will follow our previous pattern and consider the fossil fuels, the nuclear fuels, and those three "others."

TABLE 2-9
U.S. Energy Stockpiles (Q Calories)(a)

	Category	
Fuel	**Reserves**	**Ultimately Recoverable**
Coal	2,380	2,380(b)
Oil	78	753
Natural Gas	75	621
Uranium	11	88
Oil Shale	240-900	1,520-2,180
Total	**2,784-3,444**	**5,362-6,022**

Source: P.K. Theobald, S.P. Schweinfurth, and D.C. Duncan, "Energy Resources of the United States," **Geological Survey Circular 650**, Washington, D.C., 1972.

(a) Q (quadrillion, 10^{15}) Calories.
(b) No additional discovery is expected but new recovery techniques could add significantly to this total.
(c) Includes "by-product" at under $10 per ton (See Table 2-7).

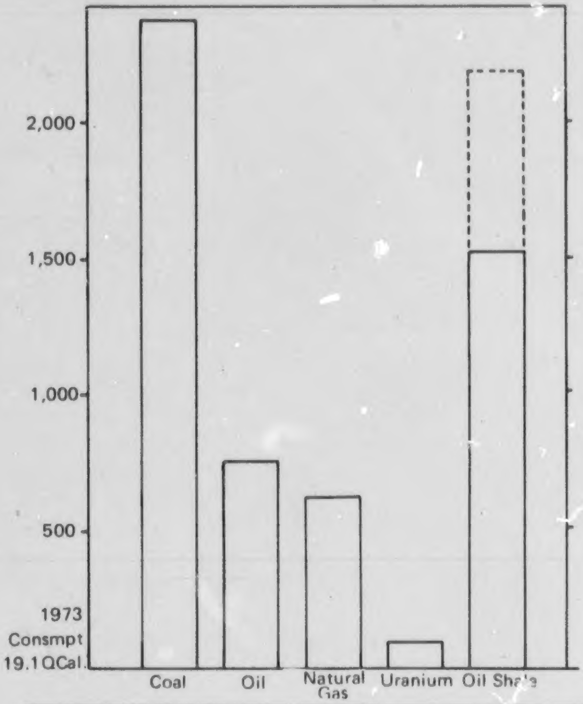
The Fossil Fuels

The world also depends heavily on the fossil fuels. On a percentage basis (1972 data) the world drew on the various sources in the percentages shown in Table 2-10. Only water power of the non-fuel sources made an appreciable contribution, 7.4 percent to fossil fuel's 92.2 percent. It is thus important to look at the size of the world's stockpiles of coal, oil, and natural gas and to also look beyond these traditional forms to oil shale and tar sands.

We show these resource data in two different ways. Figure 2-14 shows the total world "recoverable resources" of each of these five types of fossil fuels. In this presentation we have already built in the recovery factors, 50 percent for coal, 35 percent for oil, etc. discussed earlier. The restrictions of price and availability (the depth of coal seams, etc.) have also been taken into account. As was the case with United States resources, we see that coal overshadows all others, followed by the still questionable resource of oil shale.

Figure 2-15 compares the have and have-not regions of the world. The recoverable resources of the United States in the five categories (coal, oil, etc.) we used previously are compared with the eight other continental areas. Several facts stand out. In particular, we see that the superpowers are rich in energy resources, and we see why the Middle East is so concerned about its oil; it has no other energy resource.

FIGURE 2-13
U.S. Ultimately Recoverable Resources



Nuclear Fuels

Other countries are looking to the nucleus for help in the energy crunch also. By 1980 it is expected that the importance of the world's use of nuclear energy will have grown from the 0.3 percent of Table 2-10 to 4.7 percent. It is thus of importance to judge this stockpile also.

Table 2-11 shows the major landlords of uranium reserves. The dominance of the United States in this picture is due in part to the more thorough search which has taken place here.

TABLE 2-10
World Energy Consumption by Source, 1972

Source	Q Calories[(a)]	Percent of Total
Coal	16.3	32.5
Oil	22.4	47.3
Natural Gas	10.8	18.0
Hydro	1.0	2.0
Nuclear	0.2	0.3
Total	**50.7**	

Data from: **Energy Facts**, Science Policy Research Division, Congressional Research Service, Library of Congress, Washington, D.C., 1973.

(a) Q (quadrillion, 10^{15}) Calories.

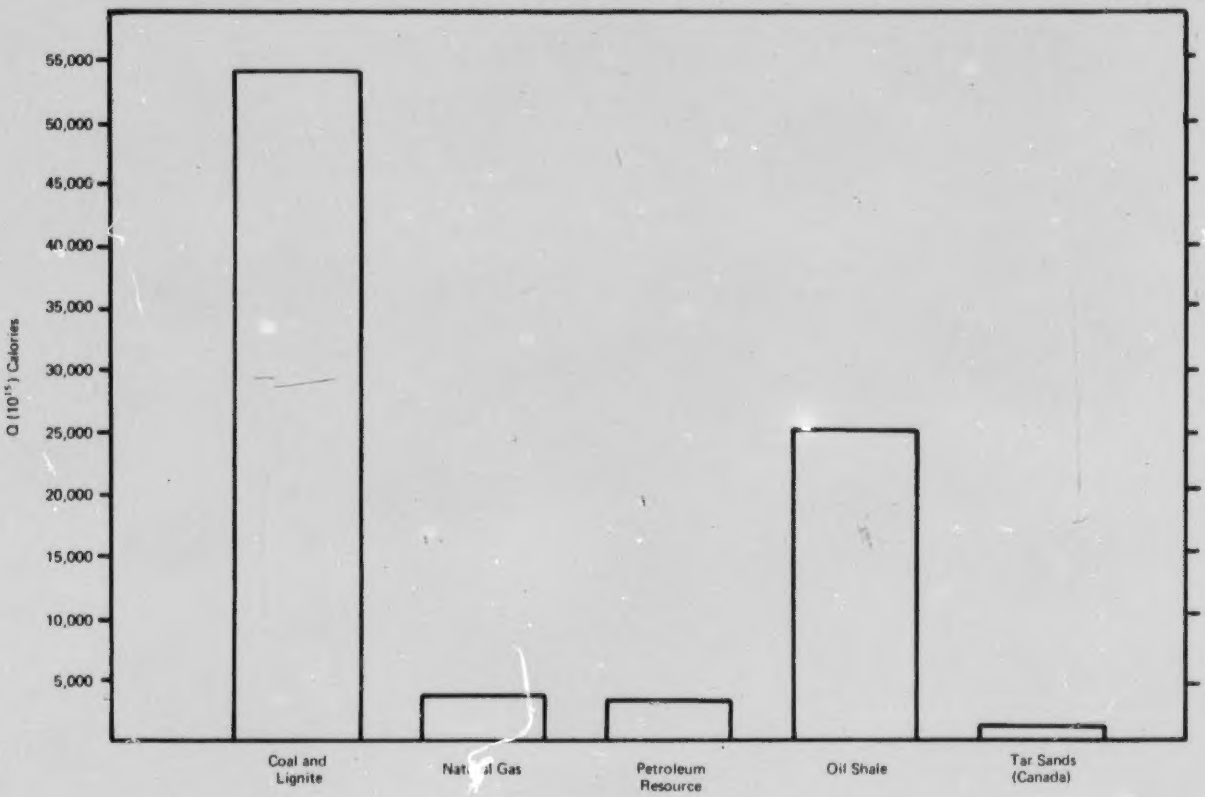
To give comparison data, we calculate, in Table 2-12, the world uranium resources in terms of Calories, based on the same conversion factors we used earlier in Table 2-7 for domestic uranium. It should be said, even more firmly in this case, that these are estimates. Only the United States has been reasonably well explored for uranium, and resources in the Communist countries are not even known.

The world also has enormous supplies of thorium. Table 2-13 shows the amount of this rare metal available at under $10 per pound already known to exist or inferred in various parts of the world. We see that we have already, without thorough exploration, discovered almost as much cheap thorium as we have cheap uranium.

The Other Sources

The world shares in the distribution of the three "other" sources — tidal, geothermal, and water power. The first of these is not very important globally. There is a tidal plant on France's Brittany Coast, on the Rance estuary, which produces 240 Mw of electric power from 24 generators. A second tidal generator is reported to

FIGURE 2-14
Remaining Recoverable Fossil Fuel Resources, Worldwide



Source: "Fossil-Fuel Resources," R. Williams, Chapter 2, in Energy and Human Welfare, Volume II, Commoner Boksenbaum and Corr (Riverside, New Jersey: MacMillan Information, 1975.

be in existence in Siberia. An estimate of the maximum power and energy available from various regions is given in Table 2-14. The total power capacity in this estimate is about the same as the United States hydroelectric power capacity in 1970.

Geothermal energy: This source has much potential importance globally. In 1972, seven countries, including the United States, produced electricity from geothermal steam-driven turbines; the world geothermal power capacity totaled some 800 Mw, or about 0.08 percent of the total world generating capacity. Interest is growing rapidly, however, and there are now perhaps 20 countries engaged in developing this energy source.

Only the crudest estimates of the available world geothermal energy can be given. Prospecting for this energy is in an early state. Sources are indicated by hot springs and geysers much as the first oil deposits were indicated by oil which leaked to the surface. Only recently has air exploration with heat sensing (infrared) cameras begun to be employed.

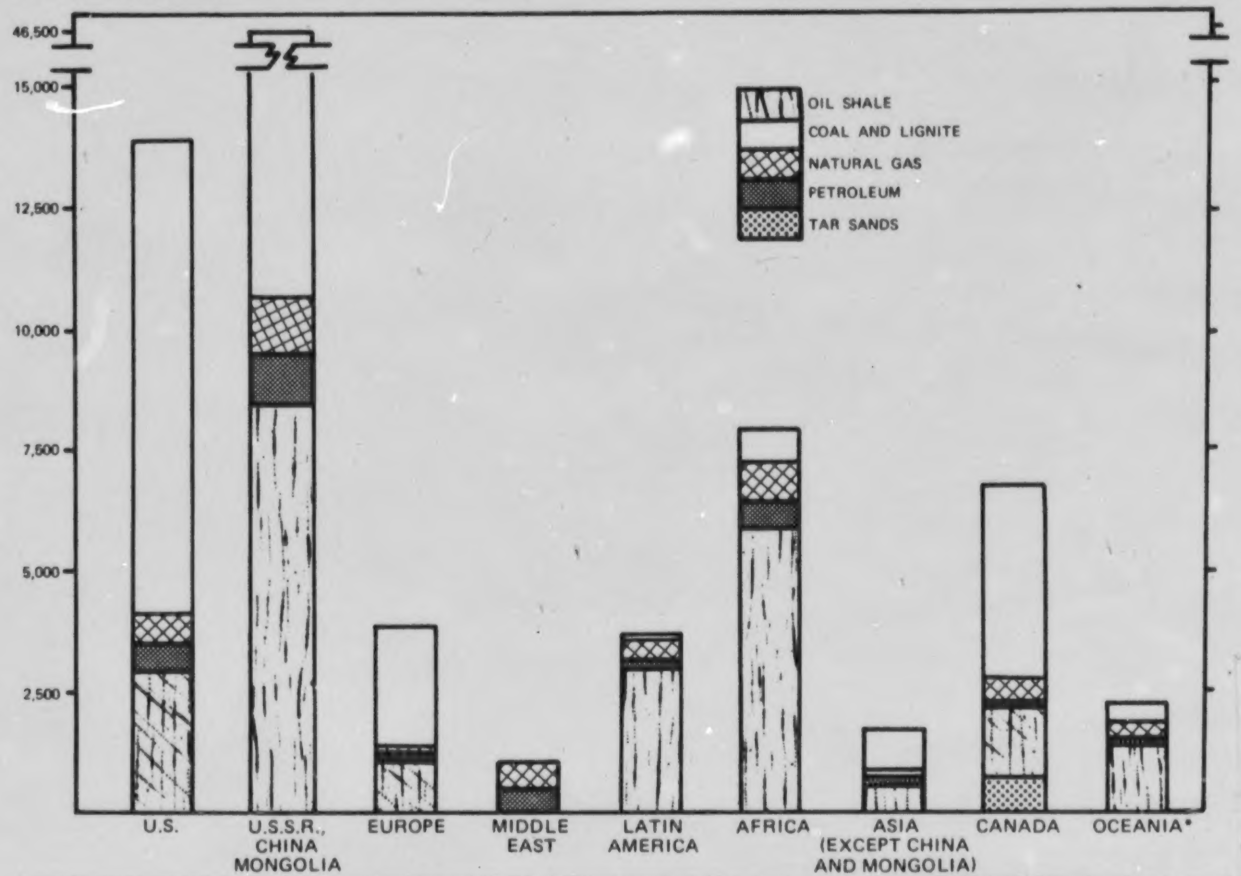
Geothermal energy is closely associated with the volcanically active, earthquake prone regions of the earth's crust. It will be found along this continent's western edge, for instance, or along the Rift Valley in Africa and its extension up into the Middle East. Individual countries may turn out to be rich in the resource. It is believed that two-thirds of Turkey has geothermal potential and that one Ethiopian field could produce enough electricity to take care of all the electric needs of present-day Africa.

TABLE 2-11
Global Distribution of Uranium Reserves[a] (in thousands of tons)

Country	Amount	Percent
United States	330	29
S. and S.W. Africa	300	26
Canada	236	20
France, Gabon, Niger	124	11
Australia	92	8
Other (excepting Communist Bloc)	68	6
Total	**1,150**	

[a] $10 per pound or less; Data from: AEC, WASH 1535, 1974.

FIGURE 2-15
Remaining Recoverable Fossil Fuel Resources by Region



Source: R. Williams, "Fossil-Fuel Resources," Chapter 2, in Energy and Human Welfare, Volume II, Commoner, Baksenbaum and Corr (Riverside, New Jersey: MacMillan Information, 1975.

*Oceania: Lands of the Central and South Pacific, including Micronesia, Melanesia, Polynesia (including New Zealand), Australia, and the Malay archipelago.

For a world-wide accounting we turn to one made by D.E. White of the U.S. Geological Survey. He estimates that a total of 10^{19} Calories of heat energy in hot water or steam sources were present above a depth of 10 km (6.6 miles). If 1 percent of this were used at a conversion efficiency (to electric energy) of 25 percent, it could produce 60,000 Mw of electric power over a period of 50 years. This is 60 times the present installed geothermal capacity but is only about the size of the tidal resources of Table 2-14, and a little larger than the total United States hydropower generation.

White's estimates are not the most optimistic ones and the new interest in this source of free energy may develop data that will prophesize a more important future. The total contribution of geothermal energy, however, will be a small fraction of the world's total consumption of electric energy.

Water power: The world has made much use of its water power, but it has been erratic. Canada and Norway, for instance, generate a large percentage of their electric power from their abundant fast-flowing streams, while the African countries have developed very little of the potential of theirs.

A summary of world water-power capacity is provided by Table 2-15 which shows both the power capacity for the various regions and the amount of that capacity that has been developed (as of 1962). It is clear that only North America and Western Europe are using their resources to a significant fraction of their potential. It is also clear that South America and Africa, which, as we saw from Figure 2-15, are not blessed with fossil-fuel resources, are rich in water power. The past decade has seen the beginning of plans to utilize this energy asset in those regions.

Summary

The energy resources we have considered in this chapter are of two forms. Some are best described as energy flows — power — and others as stockpiles of stored energy. Solar and tidal energy fit into the first category; we have somewhat arbitrarily put geothermal energy, along with chemical and nuclear energy, into the latter.

TABLE 2-12
World Uranium Resources

Category	Amount (Thousands of tons)	(Q Calories(a))
Reserves (under $10 per pound)	826	36
Estimated Additional (under $10 per pound)	743	33
Submarginal Identified ($10-$30 per pound)	1,358	60
Total Identified and Inferred (under $30 per pound)	4,890	216

Source: Office of Economic Development, 1967.

(a) Q (quadrillion, 10^{15})

TABLE 2-13
World Thorium Resources(a)
(in thousands of tons of ThO_2)

Country	Reasonably Assured	Possible Additional	Total
India	300	250	550
U.S.	65	335	400
Canada	100	155	255
Africa	50	50	100
Australia	10	——	10
Brazil	10	20	30
Total	**535**	**810**	**1,345**

(a)At $10 *per pound* or less; data from AEC, WASH 1535, 1974.

TABLE 2-14
Maximum World Tidal Power Capacity

Location	Average Power Potential (Mw)(a)	Potential Annual Energy (B kw-hr)(b)
Bay of Fundy	29,000	255
Argentina	5,870	52
England	1,700	15
France	11,100	98
U.S.S.R.	16,000	140
Total	**63,800**	**560**

Source: Brian J. Skinner, **Earth Resources** (Englewood Cliffs, New Jersey: Prentice Hall,) 1968.

(a)Megawatts (million, 10^6 watts)
(b)Billions of kilowatt-hours.

TABLE 2-15
World Water-Power Capacity
(in thousands of Mw)(a)

Region	Potential	Percent of Total	Amount Developed
North America	313	11	59
South America	577	20	5
W. Europe	158	6	47
Africa	780	27	2
Middle East	21	1	—
Southeast Asia	455	16	2
Far East	42	1	19
Australia	45	2	2
U.S.S.R., China, and Satellites	466	16	16
Total	**2,857**		**152**

Source: Brian J. Skinner, **Earth Resources** (Englewood Cliffs, New Jersey: Prentice Hall) 1968.

(a)Mw = megawatts (million, 10^6 watts).

These energy flows, or continuous sources as we sometimes term them, are all large enough to make useful contributions to our needs. One of them, solar power, could take care of us now and in years to come. However, we have developed little in the way of technology to allow use of these forms of free power and depend almost exclusively on energy from our depletable stockpiles. It is on the assessment of these stockpiles, for the United States and the world, that we focused this chapter.

The relevant data are summarized graphically in Figures 2-13 and 2-14. In both the United States and the world, coal is the largest stockpile. There is at least 10 times more coal (30 times more in the U.S.) than of oil or gas, although if the production of oil from oil shale becomes practical, this resource will rival that of coal. We also found, somewhat surprisingly, that the stockpile of uranium, due to our present inefficient conversion of its energy to electrical form, is not a large one. Improvement in conversion techniques and increased exploration will probably change that part of the picture.

The data of this chapter give us some idea of the size of our energy stockpiles. The next question would seem to be, "How long will they last?" Before we can answer we must have some information about the use of these fuels, and that will be the subject of the following chapter.

CHAPTER 3

The Flow of Energy

The Flow of Energy

In the previous chapters we became familiar with the primary sources of energy, the sizes of kinetic energy flow, and the stockpiles of potential energy available to us. It is now time to look more closely at energy in the service of man, to follow energy from these primary sources through our industrial system. We will be interested in the amount of energy that goes into each of our major consuming sectors as well as the form of energy used (whether it is electric, chemical, etc.). Most important, we will want to know the efficiency with which it is used. All this information will be pertinent when we try to design strategies for energy conservation in a later chapter. Those sectors in which large amounts of energy are used inefficiently will be the prime targets.

This chapter, therefore, has two distinct parts. In the first half we survey the pattern of energy consumption in this country and add on some of the gross features of world energy consumption. In the latter half we consider the question of the efficiency of the most important energy conversions.

Consumption by Conversion

A sailboat sailing gracefully in the wind and a waterwheel grinding corn are among the few remaining examples in our complex industrial society of energy being used in its original form. In almost all other cases when we speak of "using" energy, we are really talking about converting it from one form to another. Energy is not consumed in our system, it flows through it, with only the absolute amount (the total Calories) remaining (as the first law tells us) the same.

We symbolize this flow in a crude way by Figure 3-1. We classify energy in three different ways: as primary sources, which we described in Chapter 1 and measured in Chapter 2, as intermediate forms, and as end uses. Figure 3-1 is not a precise diagram; thermal energy, for instance, is an end use in home heating or steel-making, but an intermediate form in the automobile engine. In the generation of electricity, several intermediate forms of energy occur. In a coal-fired generating plant the primary (chemical) energy of coal is converted to thermal energy in the furnace, converted to mechanical energy is converted to electric energy by mechanical energy is converted to electrical energy by the generator. The nuclear generation of electricity is also a multistep conversion.

As we have said, the primary sources occur both as kinetic and potential energy; solar, geothermal, and tidal are kinetic, while chemical and nuclear are potential. The intermediate forms are all kinetic, they are energy in transit from one form to another. Electric energy is the prototype intermediate form; it must always be converted to be useful to man.

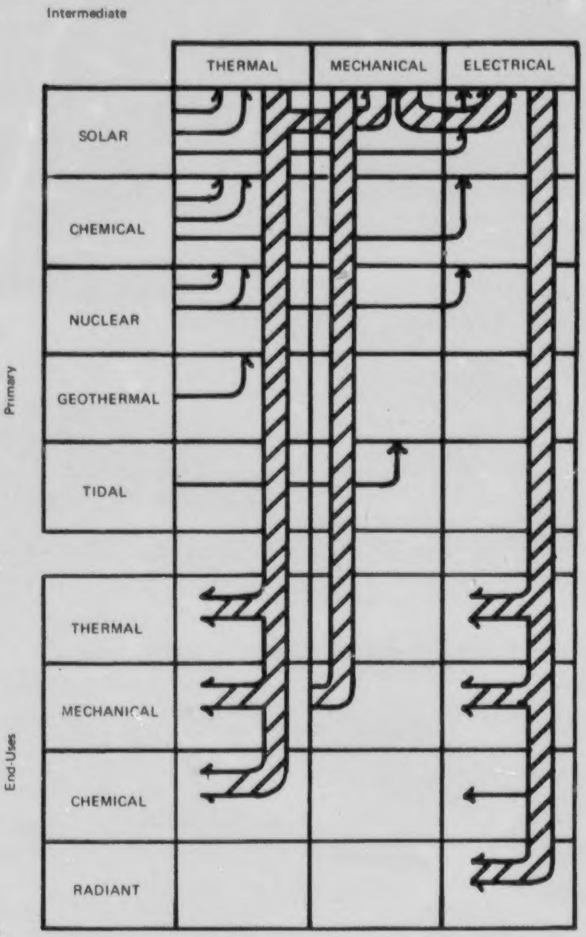
The end uses, as were the sources, are split between kinetic and potential types. When we use energy to produce work, light (or other forms of radiant energy) or heat, we are using kinetic energy. A significant amount of the energy expended in the industrial sector goes into the rearranging of molecules and thus into chemical potential energy. Some of the energy used in refining raw materials is stored in this way; plastics manufacture is an example. This stored energy is then released when plastics burn or metals rust.

With the qualification that consumption means conversion, we will now give a quantitative dimension to the qualitative picture of Figure 3-1.

Patterns of Consumption

In 1973 we consumed, on the average, 52 Trillion (T) Calories of energy per day in this country. (This was reduced to 51 T Calories in 1974.) How was this energy used? The only reported thorough study of this question was made by the Stanford Research Institute for the U.S. Office of Science and Technology using 1968 as the reference year. The qualitative results of this study, as far as the percentages expended in the various sectors are concerned, apply with little change today, although the total amount consumed in each category has increased.

FIGURE 3-1
Paths of Energy Conversion



Legend: The smaller lines ⤴ indicate relatively unimportant conversions.

In 1968 a total of 15.3 Quadrillion (Q) Calories of energy was consumed in this country. (The total in 1973 was 18.9 Q Calories and in 1974, 18.5 Q Calories.) This energy was divided in the percentages shown in Figure 3-2 among the four major sectors: Residential, Commercial, Industrial, and Transportation. This figure also shows the major end uses of the energy within each sector. Electric energy gives us a problem since two-thirds of the energy used to generate it is wasted. In Figure 3-2 we assign to each sector not just the electricity consumed but all of the primary energy (from fossil or nuclear fuels) used to generate this electricity.

Another way of looking at energy consumption is by a breakdown of end use. Table 3-1 provides the percentage of total of the top 12 end uses. Of the 100 or so ways in which energy is used in our economy, these 12 accounted for 97 percent of the total in 1968. The top four alone accounted for 71 percent. We see that heat energy in one form or another dominates this list of end uses, accounting for about half of the total. Mechanical work (transportation and electric drive) accounts for an additional third.

An important end use to remember is the one called "feedstocks." The fossil fuels are not only sources of energy, but also provide raw materials for many industrial products, from asphalt to synthetic fibers. If these raw materials are evaluated at their energy equivalent, they account for about 6 percent of the 1968 total. Their percentage share is increasing rather rapidly and depletion of the fossil fuel resources is, perhaps, more threatening in the long run on this account than from the point of view of energy. It may be easier to find alternate sources of energy than to replace the precious and complex molecules nature has stored for us in coal and the petroleum products.

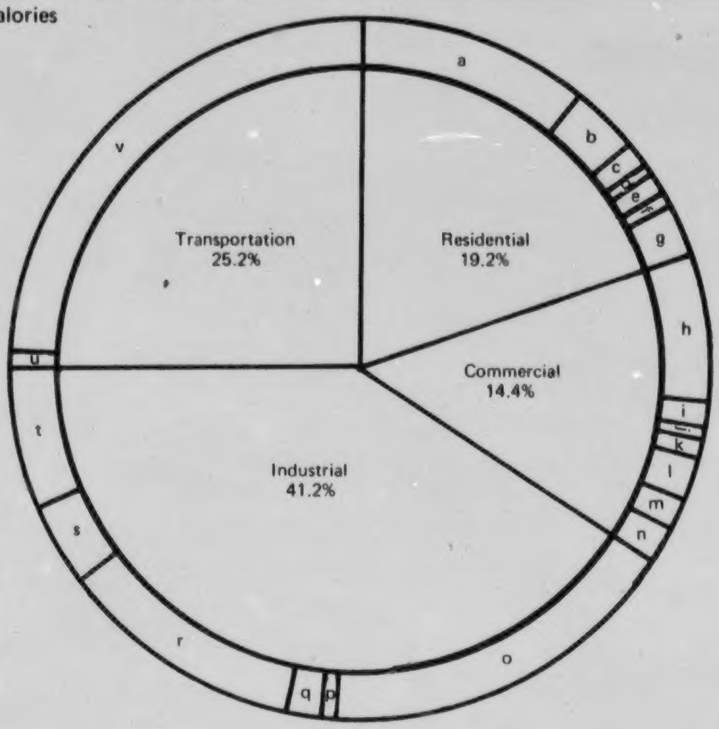
The Electric Utilities as a Consuming Sector

In the following sector breakdowns of energy consumption it will be useful, for several reasons, to pay special attention to electric energy. Its consumption shows the fastest growth of any of the energy forms and this has led to shortages — blackouts and brownouts. Its generation and transmission are very inefficient and this leads both directly and indirectly to many of the environmental problems we consider later on.

In order to single out the amount of energy used in the generation of electricity, we show a different breakdown of consumption in Table 3-2. These 1973 data show the

FIGURE 3-2
Breakdown of U.S. Energy Consumption, 1968

Total 15.3 Q (10^{15}) Calories



Transportation	**Percent**
v. Fuel	24.9
u. Raw Materials	.3

Industrial	**Percent**
t. Other	7.5
s. Feed Stocks	3.6
r. Direct Heat	11.4
q. Electrolytic Processing	1.2
p. Electric Drive	.8
o. Process Steam	16.7

Residential	**Percent**
a. Space Heating	11.0
b. Water Heating	2.9
c. Cooking	1.1
d. Clothes Drying	.3
e. Refrigeration	1.1
f. Air-conditioning	.7
g. Other	2.1

Commercial	**Percent**
h. Space Heating	6.9
i. Water Heating	1.1
j. Cooking	.2
k. Refrigeration	1.1
l. Air-conditioning	1.8
m. Feed Stocks	1.6
n. Other	1.7

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

percentages of the primary sources (the fossil fuels, hydropower, and nuclear energy) used by the various sectors (residential and commercial are combined) and the electric utilities. In that year the utilities used 26 percent of the total primary energy, but the electricity produced amounted to only 8 percent of the total energy consumed. In 1974 these percentages were, respectively, 27 and 8.7.

The various sources of energy to the utility sector are identified in Table 3-2. Then the contributions from these sources are displayed as percentages in Table 3-3. Coal is the major source and, even with the rapid growth expected in nuclear generating facilities, will continue to be the major source until the 1990s.

Only three of the four consuming sectors are important consumers of electricity; 31 percent of it was used in the residential sector, 24 percent in the commercial sector, and 45 percent in the industrial sector. Transportation used only about 5 Million (M) kw-hr out of a total of 1,330 M kw-hr used that year.

In the following sections we provide details of the end uses of this electricity within each sector.

Residential Consumption of Energy

The 2.94 Q Calories of energy used by the residential sector in 1968 were divided among the various end uses in the percentages shown in Table 3-4. We also show 1960 data to emphasize the changes that are taking place.

Of the various end uses, "comfort energy," the energy used to heat and cool living space, accounts for almost two-thirds of the total. The most rapid growth was in air conditioning, but consumption by all appliances, except cooking, is increasing.

In the residential sector natural gas, which is used in space and water heating, cooking, and in some clothes driers, is the most important fuel (as is shown in Table 3-5). Electric energy is next in importance, if we include the two-thirds which is lost in its generation.

The end uses of electric energy in the residential sector are shown in Table 3-6 along with the record of growth from 1960 to 1968. The rapid increase in electric space heating is worth special note. Only about 3 million homes, 7 percent of the total, used electric heat in 1968 while 43 percent used fuel oil and 50 percent natural gas. This total had increased to 4 million by 1970 and about one-third of the new homes built that year were heated electrically. The Federal Power Commission's projection (see Figure 3-3) is for a continued increase to 12.5 million in 1980 and 24 million in 1990. They anticipate that 40 percent of the homes constructed from 1970-1980 will be all-electric as will half of those constructed in 1980-1990. This is one of the changes that is bringing about the rapid growth in electricity demand we shall examine later.

It is also helpful in analyzing the consumption of electric energy tc have data on the power rating and the average yearly consumption of energy of the various popular household appliances. We show that data in Table 3-7.

Overall energy use in the residential sector grew at an annual rate of 4.3 percent from 1960 to 1968. This rate of growth causes a doubling of total consumption every 16 years.

TABLE 3-1
Major End Uses of Energy, 1968

	Percent of Total
Transportation (fuel; excludes lubes and greases)	24.9
Space Heating (residential, commercial)	17.9
Process Steam (industrial)	16.7
Direct Heat (industrial)	11.5
Electric Dirve (industrial)	7.9
Feedstocks, Raw Materials (commercial, industrial, transportation)	5.5
Water Heating (residential, commercial)	4.0
Air-conditioning (residential, commercial)	2.5
Refrigeration (residential, commercial)	2.2
Lighting (residential, commercial)	1.5
Cooking (residential, commercial)	1.3
Electrolytic Processes (industrial)	1.2
Total	97.1

Source: **Patterns of Energy Consumption in the United States**, Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

FIGURE 3-3
Electrically Heated Homes in the U.S.

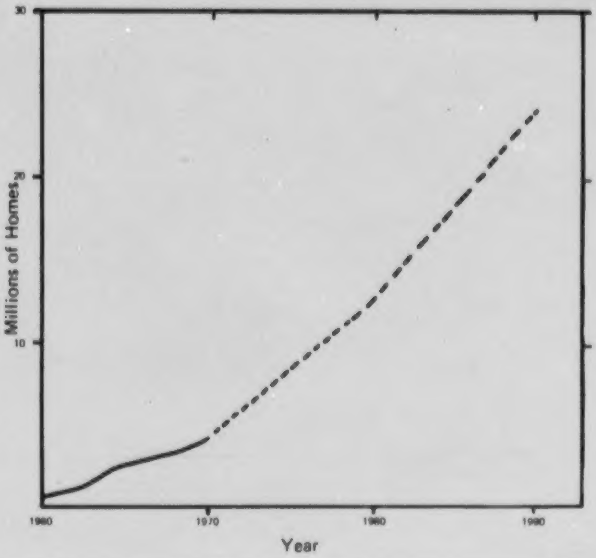


TABLE 3-2
Energy Consumption by Sector, 1973 (Q Calories)(a)

Consuming Sector	Coal	Natural Gas	Primary Source Petroleum	Hydropower	Nuclear	Total Energy	Percent of Total
Household and Commercial	.09	2.02	1.77	—	—	3.89	20.5
Industrial	1.12	2.74	1.53	—	—	5.39	28.4
Transportation	—	0.21	4.53	—	—	4.73	24.9
Electric Utilities	2.19	0.98	0.87	0.73	0.22	5.00	26.3
Total						19.01	100.00

Source: Bureau of Mines, U.S. Department the Interior.

(a)Q (quadrillion, 10^{15}) Calories.

TABLE 3-3
Sources of Electric Power, 1973

Source	Percent of Total
Coal	45.5
Natural Gas	19.8
Petroleum	17.3
Hydropower	14.7
Nuclear	4.3

Source: Bureau of Mines, U.S. Department of the Interior.

TABLE 3-4
End Uses of Energy in the Residential Sectors by Percentage

	1960	1968
Space Heating	60.8%	57.5%
Water Heating	14.5	14.9
Cooking	7.0	5.5
Refrigeration	4.6	6.0
Air-conditioning	1.7	3.7
Television	2.0	3.0
Clothes Drying	1.2	1.7
Food Freezing	1.0	1.9
Other	7.2	5.8
Total	100.0%	100.0%

Source: **Patterns of Energy Consumption in the United States, Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.**

TABLE 3-5
Fuel Use in the Residential Sector, 1968

Fuel	Physical Amount(a)	Energy (TCal.)(b)	Percent of Total
Natural Gas	4,473 B ft^3	1,163	39.6
Fuel Oil and Kerosine	422 M bbls	633	21.6
Propane, Butane etc.	173 M bbls	173	5.9
Electricity (including loss)	112 B kw-hr	964	32.9
		2,933	100.0

Source: **Patterns of Energy Consumption in the United States, Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.**

(a)B ft^3 = billion cubic feet; M bbls - million barrels;
B kw-hr = billion kilowatt hours.

(b)T Cal = trillion (10^{12}) Calories

TABLE 3-6
Electric Energy Consumption in the Residential Sector

End Use	Amount (M kw-hr)(a)	Percent of Total	1960-1968 Percentage Growth
Refrigerator	73.3	18	105
Water Heating	65.2	16	44
Space Heating	48.1	12	466
Air-conditioning	45.2	11	221
TV	37.6	9	116
Cooking	28.1	7	32
Food Freezer	23.5	6	167
Clothes Dryer	15.0	4	120
Lighting	44.0	11	
Other	27.3	7	16
Total	407.4		

Source: **Patterns of Energy Consumption in the United States, Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.**

(a)M kw-hr = million kilowatt-hours.

Consumption of Energy in the Commercial Area

The commercial category is a catch-all, including everything that is not residential, industrial, or transportation. In 1968 the commercial buildings, small businesses, hotels, restaurants, schools, colleges, etc., that comprise this category used 2.21 Q Calories, 14 percent of the total. A breakdown by end use is given in Table 3-8. If we set aside "asphalt and road oils," which are raw material uses of these fuels, the largest use is, again, of comfort energy. The fastest growing sector, "other," includes lighting, elevators, and such, and is thus mainly powered by electricity.

A breakdown of fuel consumed in the commercial sector is provided by Table 3-9. We see that electricity is already the primary energy form if generation losses are added in. Specific end uses of this electricity are shown in Table 3-10. Here we see the importance of the "other" category, which accounts for 35 percent of the electricity consumed. More than half of that electric energy goes into lighting. From Table 3-10 we see that this "other" category is the most rapidly growing one.

Commercial energy consumption is growing more rapidly than any other sector. Its annual growth rate (for 1960 to 1968) was 5.4 percent, corresponding to a doubling every 13 years. Residential and commercial combined consumed 6.39 Q Calories in 1973 as compared to 5.15 Q Calories in 1968. This is a 24 percent increase in five years. In 1974, the consumption in this combined category was 6.33 Q Calories.

TABLE 3-7

Approximate Power Rating and Estimated Annual Energy Consumption of Electric Appliances Under Normal Use

	Average Wattage	Est. kw-hr[a] Consumed Annually
FOOD PREPARATION		
Blender	386	15
Broiler	1,436	100
Carving Knife	92	8
Coffee Maker	894	106
Deep Fryer	1,448	83
Dishwasher	1,201	363
Egg Cooker	516	14
Frying Pan	1,196	186
Hot Plate	1,257	90
Mixer	127	13
Oven, Microwave (only)	1,450	190
Range		
with Oven	12,200	1,175
with Self-cleaning Oven	12,200	1,205
Roaster	1,333	205
Sandwich Grill	1,161	33
Toaster	1,146	39
Trash Compactor	400	50
Waffle Iron	1,116	22
Waste Disposer	445	30
FOOD PRESERVATION		
Freezer (15 cu ft)	341	1,195
Freezer		
(Frostless 15 cu ft)	440	1,761
Refrigerator (12 cu ft)	241	728
Refrigerator (frostless 12 cu ft)	321	1,217
Refrigerator/Freezer		
(14 cu ft)	326	1,137
(frostless 14 cu ft)	615	1,829
LAUNDRY		
Clothes Dryer	4,856	993
Iron (hand)	1,008	144
Washing Machine (automatic)	512	103
Washing Machine (non-automatic)	286	76
Water Heater	2,475	4,219
(quick recovery)	4,474	4,811
COMFORT CONDITIONING		
Air Cleaner	50	216
Air-conditioner (room)	860	860*
Bed Covering	177	147
Dehumidifier	257	377
Fan (attic)	370	291
Fan (circulating)	88	43
Fan (rollaway)	171	138
Fan (window)	200	170
Heater (portable)	1,322	176
Heating Pad	65	10
Humidifier	177	163
HEALTH & BEAUTY		
Germicidal Lamp	20	141
Hair Dryer	381	14
Heat Lamp (infrared)	250	13
Shaver	14	1.8
Sun Lamp	279	16
Tooth Brush	7	0.5
Vibrator	40	2
HOME ENTERTAINMENT		
Radio	71	86
Radio/Record Player	109	109
Television		
Black-&-White		
Tube Type	160	350
Solid State	55	120
Color		
Tube Type	300	660
Solid State	200	440
HOUSEWARES		
Clock	2	17
Floor Polisher	305	15
Sewing Machine	75	11
Vacuum Cleaner	630	46

* Based on 1,000 hours of operation per year. This figure will vary widely depending on area and specific size of unit.

Source: Edison Electric Institute.

[a] Kw-hr = Kilowatt-hour.

The Industrial Sector

The big energy consumer is the industrial sector; 6.31 Q Calories in 1968, or 41 percent of that year's total consumption. This sector's share has been decreasing slowly (although total consumption has increased). This trend is expected to continue. In 1973 the industrial sector used 7.44 Q Calories, 39 percent of the total, and in 1974, 7.42 Q Calories, 40 percent of the total.

Table 3-11 shows the percentages of industrial energy supplied by the various fuels. Coal retains a significant industrial market although its importance is declining — from 27 percent of the market in 1960 to 18 percent in 1968. In 1974, coal's share was only 14 percent. Natural gas made up 34 percent of the market in 1960 and 37.3 percent in 1968. Even with the natural gas shortage its percentage share of the industrial market grew from 36.9 percent in 1973 to 37.9 percent in 1974. Electricity grew from about 20 percent in 1960 to 23 percent in 1968. Its 1974 share of 27.9 percent is up only slightly over the 1973 share of 27 percent. Table 3-12 identifies the energy-intensive industries. These six industries account for two-thirds of industrial energy consumption. This table also identifies the primary energy source. The two major users, the primary metals

TABLE 3-8
End Uses of Energy in the Commercial Sector by Percentage

	1960	1968
Space Heating	54.2%	47.7%
Asphalt and Road Oils	12.8	11.2
Water Heating	9.5	7.5
Air-conditioning	10.0	12.7
Regrigeration	9.3	7.6
Cooking	1.7	1.6
Other	2.5	11.7
Total	100.0%	100.0%

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

TABLE 3-9
Fuel Use in the Commercial Sector, 1968 data

Fuel	Physical Amount[a]	Energy (T Cal)[b]	Percent of Total
Coal	23.4 M tons	143	6.5
Oil	405 M bbls	607	27.5
Natural Gas	1,792 B ft^3	466	21.0
Electricity (incl. losses)	870 B kw-hr	748	33.8
Asphalt (road oil, etc.)		248	11.2
Total		2,212	

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

[a] M tons = million tons; M bbls = million

[a] M tons = million tons; M bbls = million barrels; B ft^3 = billion cubic feet; B kw-hr = billion kilowatt hours.

[b] T Cal = trillion (10^{12}) Calories

TABLE 3-10
Electric Energy Consumption in the Commercial Sector

End Use	Amount (M kw-hr)[a]		Percent of Total		1960-1968 Percentage Growth
Water Heating	24.6		7.8		19
Refrigeration	71.5		22.6		36
Air-conditioning	108.6		34.3		84
Cooking	2.3		0.7		57
Other	109.6		34.6		611
Lighting		59.0		18.7	
Advertising and Display Lighting		7.9		2.5	
Elevators		11.7		3.7	
Fans and Air-handling Equipment		10.3		3.3	
Pump and Motors		5.3		1.7	
Miscellaneous		15.2		4.7	
Total	316.5		100.0		106

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

[a] M Kw-hr = million kilowatt-hours

industries (steel, aluminum, copper, etc.) and the chemical industries, differ significantly in fuel requirements. Steel companies, for instance, use large amounts of coal, while the chemical companies are major users of petroleum.

An important cause of the declining percentage of the total consumption in the industrial sector is the improvement in the efficiency of production. Said otherwise, it now takes less energy to produce a ton of steel, paper, etc. than it did a decade ago, 7.6 M Calories per ton of steel in 1960 as against 6.6 M Calories in 1968, and 8.6 M Calories in 1960 but only 6.6 M Calories in 1968 for a ton of paper.

The energy cost of materials: When we look later on at strategies for energy conservation, it will be important to know how much energy is needed to produce a pound of steel, plastic, paper, etc. This information will guide us not only in modifying our consumption patterns, but will also suggest categories in which recycling may be important. We have gathered together in Table 3-13 these data for a large variety of manufactured products. One interesting group of materials in this list is the plastics. We see that they require more energy per pound than steel, and certainly more than paper with which they often compete. Much of this energy could be recovered by burning the plastics to produce steam. They contain as much as 5,000 Calories per pound

TABLE 3-11
Industrial Fuels (by percentage)

Energy Source	Percent of Total 1960	1968	1974
Coal	26.7	22.6	14.3
Natural Gas	34.3	37.3	37.9
Petroleum Products	19.3	18.0	19.8
Electricity	19.7	22.6	27.9

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972, and Bureau of Mines, U.S. Department of the Interior.

TABLE 3-13
Energy Expenditure in Manufacture of Various Materials (M Calories per ton)[a]

Material	Energy
Metals	
Steel	6.5
Aluminum	18.8 (41.8)[b]
Lead	7.8
Copper	10.0
Zinc	11.5-13.
Cement, Clay, Glass	
Cement	2.5
Glass	
Plate & Bottles	3.5-4.5
Technical Glassware	13.5
Handmade Glassware	20.
Porcelain & China	10.
Tile	1.
Bricks	.25-1.5
Plastics	
Polyethylene	34.
Polypropylene	36.
Polyvinylchloride	26.
Polystyrene	11.

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

[a] M (million, 10^6) Calories per ton.

[b] The figure in parentheses includes the electric conversion losses.

TABLE 3-12
Fuel Use by the Six Energy Industries, 1968 (in T Calories)[a]

Industry Group	Coal	Natural Gas	Petroleum Products	Electricity	Total Energy
Primary Metals	571	213	77	323	1,325
Chemicals and Allied Products	167	305	357	407	1,234
Petroleum Refining and Related Industries	*	253	391	56	707
Food and Kindred Products	66	148	34	85	332
Paper and Allied Products	117	85	53	70	325
Stone, Clay, Glass, and Concrete Products	102	112	22	70	306
Subtotal	1,160	1,119	938	1,010	4,228
All Other Industries	244	1,195	180	393	2,013
Total	1,404	2,315	1,119	1,153	6,240

Source: **Patterns of Energy Consumption in the United States,** Office of Science and Technology, Executive Office of the President, Washington, D.C., 1972.

[a] T (trillion, 10^{12}) Calories.

*Included in all other industries.

(polyethylene), much more than the 2,500-3,250 Calories per pound contained in coal.

The energy cost of food: The food industry's share of the total energy was 5.3 percent in 1968 and its share is declining. It seems to be entering that cycle of improved efficiency that other industries passed through in the 1950s.

The production of food remains, however, an energy intensive process. As we saw in Chapter 5, Volume I, if all the direct and indirect energy consumed on the farm and in the processing and distribution system is considered, it takes 10 or 15 Calories of fossil fuel energy to produce 1 Calorie of food energy.

It is also of interest to look specifically at protein, that so important constituent of food. Table 3-14 shows the energy required to produce a pound of protein in various forms. We also show the ratio of the energy input to the energy content of these foods. On an energy basis, cheese is clearly the people's choice.

The Consumption of Energy in Transportation

Transportation used 25.2 percent of the total energy in 1968, 3.83 Q Calories. Its percentage share has remained about constant (25.6 percent in 1960, 24.8 percent in 1973, and 25 percent in 1974) while total use has grown steadily (the 1973 transportation total was 4.78 Q Calories). However, the 1974 gasoline shortage and the price rise reduced use to 4.62 Q Calories.

In contrast to the other sectors, one fuel, petroleum, dominates. Gasoline, the major fuel, holds 68 percent of the market followed by jet fuels (kerosene) with 13 percent and the distillate oils (diesel) with 8 percent. The 3.83 Q Calories consumed in 1968 translates, at 1.46 M Calories per barrel, into 2.5 B bbls, more than half of the 4.5 B bbls consumed that year. The 1973 total of 4.74 Q Calories was the equivalent of 3.25 B bbls of oil, also a little more than half of that year's total.

The 25.2 percent share of energy attributed to transportation really underestimates the total energy that sector consumes, for only the direct use of fuel is taken into account. A sharper perspective on the energy intensiveness of this sector is provided by the breakdown of Table 3-15. One sees that transportation, if the amounts of energy used in refining, manufacturing, etc., are included, accounts for almost 40 percent of our total energy consumption. It is, therefore, worth our while to look briefly at the modes of transportation and at the percentages of energy consumed in each one.

There are two main purposes to transportation — moving people and moving things, or passenger transport and freight transport. A second dimension is provided by the distance moved. So we divide transportation into two categories, urban transport (less than 100 miles) and intercity transport (greater than 100 miles). The record of energy consumption (of fuel only) in each of the four categories that result from these distinctions is shown in Figure 3-4. All the curves swing upward, with the sharpest rise in urban passenger transportation (UPT).

We also show, in Figure 3-4, the Bureau of Mines projection of energy consumption growth in this sector; it is expected to increase from 3.83 Q Calories in 1968 to 10.9 Q Calories in 2000. From these data we can calculate that in these 30 years the transportation sector alone will consume 230 Q Calories of energy, the equivalent of 158 B bbls of oil. This is more oil than is present in the entire Alaskan North Slope oil field and one-fifth of the ultimately recoverable oil shown in Table 2-3. It is no wonder that transportation is a prime target for energy conservation.

TABLE 3-14
Energy for Protein Production

Food Product	Total Production Energy to Protein Ratio Cal per Pound	Production Energy to Energy Content
Meat Products	32,600	6.3
Cheese, Natural and Processed	18,800	2.6
Fluid Milk	51,200	6.1
Fresh or Frozen Packaged Fish	17,700	6.5

Source: Bruce Hannon, "Options for Energy Conservation," University of Illinois Center for Advanced Computation, **CAC Document No. 79**, June 18, 1973, pg. 17.

(a) Calories per pound.

TABLE 3-15
Total Energy for Transportation

Sector	Use	(Q Cal)(a)		% of Net Energy Input
Primary Transport (propulsion)	Automobile	1.40		
	Truck and Bus	.77		
	Jet	.41		
	Railroad	.18		
	Marine	.14		
	All Other Prop.	.40	3.79	29%
Secondary Transport (related activities)	Fuel refining, Asphalt and Road Oil, Energy	.61		
	Primary Metals Used in Transport Manufacture	.26		
	Manufacturing	.13		
	All Other Secondary	.26	1.26	9%
Total			5.05	38%

Source: "Electric Power Consumption and Human Welfare," AAAS/CEA Power Study Group, AAAS Committee on Environmental Alternatives, unpublished report, pg. III-12.

(a) Q (quadrillion, 10^{15})

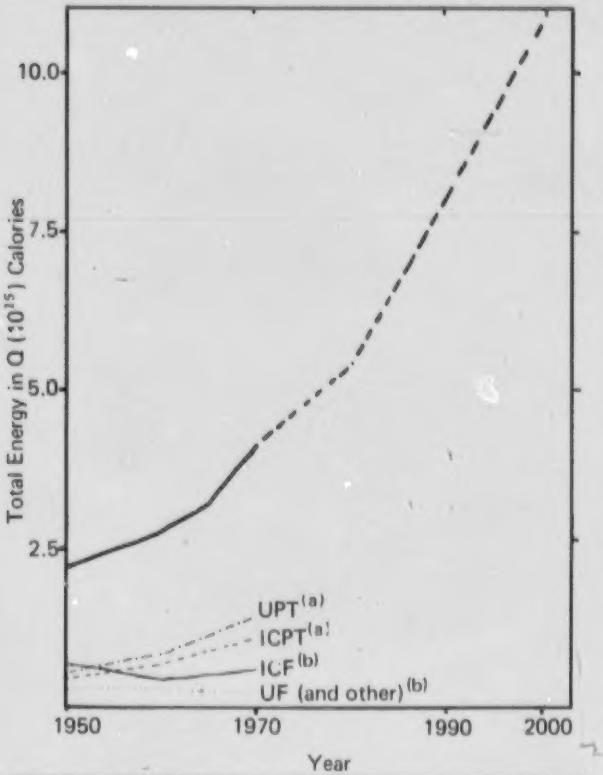
Transportation of energy: Of particular interest among the various cargoes that are shipped across this country and around the world is energy itself. The differences in the amount of energy per pound of the various fuels (see Table 1-3) and the efficiencies of the different transport modes that are available to solid, liquid, and gaseous fuel conspire to make the dollar costs per Calorie of energy transported vary significantly from mode to mode.

We have gathered the relevant data together in Figure 3-5. We see that the cheapest form of energy transport is tanker shipment of oil, hence the building of the supertankers. The bigger the tanker, the lower price per Calorie-mile. The liquid fuels, oil and LNG (liquified natural gas), are all at the bottom of the price list, reflecting the ease with which a liquid can be handled and the high energy density (Calories per pound) of these fuels. The liquid fuels are followed by coal, which is transported in specially constructed trains and then by pipeline gas.

In contrast to the apparently easy transport of electricity, we see that it is, overall, the most expensive energy to ship and that its price climbs rapidly as the distance increases. We also see that the price is reduced as the transmitting voltage is increased. At 700,000 volts, the cost per mile is less than that of oil by rail tank car. For this reason higher and higher transmission line voltages are being used.

FIGURE 3-4

Transportation Energy, with Projection to 2000



Source: Bureau of Mines, U.S. Department of the Interior

(a) UPT = Urban passenger transportation; ICPT = Intercity passenger transportation;
(b) ICF = Intercity freight transport; UF = Urban freight transport

It must be pointed out that prices are influenced by more than the energy density of the fuel and the inherent efficiency of the transport mode. A host of freight regulations and direct and indirect subsidies play roles that could cause some shifts in the rankings of Figure 3-5.

We should also comment that uranium has an energy density so much larger than any of the others its shipment costs are negligible and so are not displayed for this comparison.

With this discussion of transportation we complete our description of the consumption of energy in the United States. We will now take a brief look at where the world's energy goes.

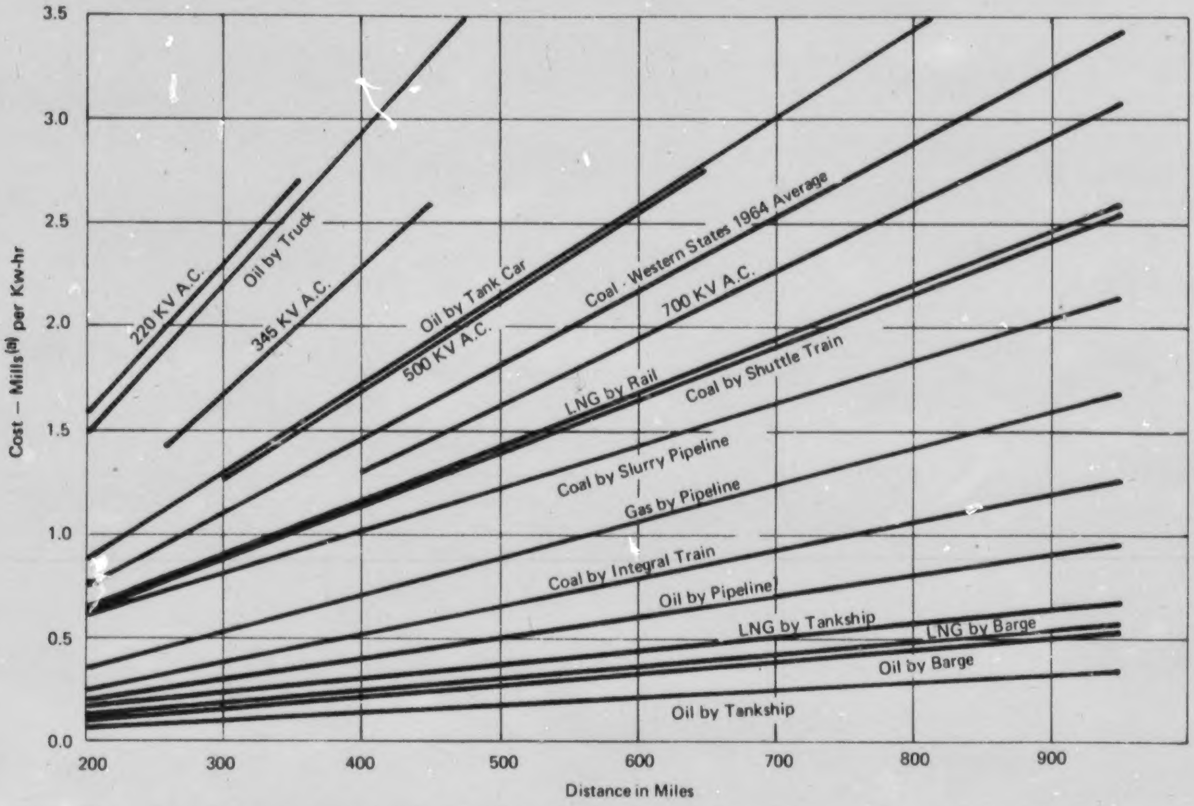
Patterns of Consumption in the World

In 1972 the total amount of energy consumed in the world was reported to be 50.7 Q Calories. The 18.2 Q Calories consumed that year in the United States, which has 6 percent of the world's population, were 36 percent of the world's total. The per capita consumption is even more unbalanced. On the average, the world citizen used 13.3 M Calories in 1972. In the United States, the per capita consumption was 87.4 M Calories, almost seven times the world average. The disparity between the United States consumption and certain countries can be even greater as is shown in Figure 3-6. The United States, for instance, has almost 60 times the per capita consumption of India. To some extent this difference between the United States and the economically underdeveloped countries is exaggerated by these data, for what is reported is commercial energy, and countries like India and Brazil use large amounts of noncommercial fuel. In India, it is estimated, 100 million tons of cow dung and vegetable waste are burned each year. This would raise her per capita consumption figure by perhaps as much as 30 percent. Even with this correction the United States per capita consumption is still 46 times greater.

In spite of the great differences between countries, we also see from Figure 3-6 that many are now showing growth in per capita energy consumption that is greater than the United States growth rate. Since their populations in some instances are also growing more rapidly than ours, the United States share of the total world energy has been dropping; from 45 percent in 1950 to 36 percent in 1960. As we can see from the data of Figure 3-6, however, it will take decades of growth for the per capita consumption in most other countries to approach ours.

We can gain some further insight into the differences by looking at the way in which energy is used in various countries. We do not have the same kind of detailed data available for the world that we have referred to for the United States. Figure 3-7 compares the energy expenditures of three industrial countries and two underdeveloped countries in each of three different

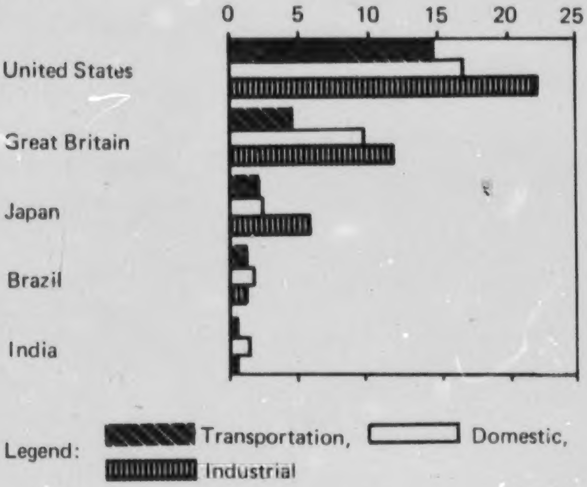
FIGURE 3-5
Average Costs of Energy Transportation



Source: "The 1970 National Power Survey, Part III," Federal Power Commission.

(a) A Mill is 0.1 cent or $0.001

FIGURE 3-7
Per Capita Consumption of Energy by Economic Sector, 1964 (in millions of calories)

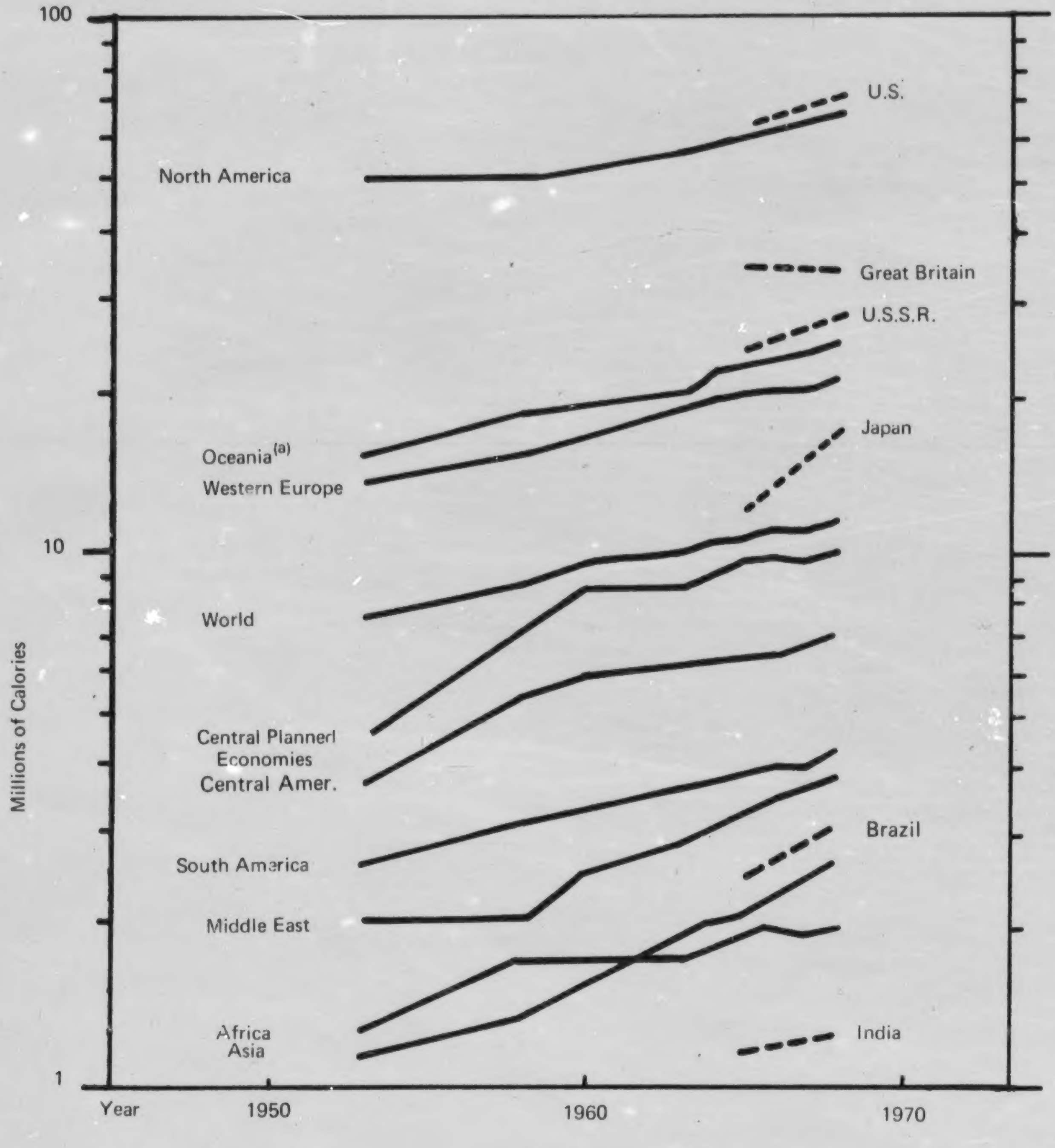


Adapted from: N.B. Guyol, **Energy in the Perspective of Geography**, (New York: Prentice Hall, 1971.).

categories (1964 data). We see that the industrially underdeveloped countries expended the greater portion of their energy on domestic needs. We also see the large energy investment in transportation in our big country. Brazil, which like the United States is big, also had a relatively large expenditure for transportation, while the smaller countries, Japan and Great Britain, showed relatively smaller transportation energy expenditure. The overriding point from the comparison of the three industrial countries is that the United States uses its energy lavishly. In Japan and Great Britain a much larger percentage of the total energy expenditure is directed into industrial production.

FIGURE 3-6

Comparison of Annual Per Capita Energy Consumption of Various Countries and Regions



Source: **1969 Statistical Yearbook,** Statistical Office of the United Nations, Department of Economic and Social Affairs (New York: United Nations) 1970, p. 324.

(a) Oceania: Lands of the Central and South Pacific, including Micronesia, Melanesia, Polynesia (including New Zealand), Australia, and the Malay archipelago.

Energy Efficiency

In tracing the energy flow through our economic system we have, so far, treated it as if the system were perfect. It is now time to look at the leaks, the losses which occur at each one of the conversions, from primary source through intermediate form (or forms) to end use.

We must make it clear from the beginning that our use of the term "loss" is meant to indicate that energy is lost for further useful conversion. It does not, of course, disappear; the First Law guarantees that. It is the Second Law, which imposes the "heat tax" on all energy conversions, that is important here.

Irreversibility

A concept from physics that is useful to us is that of irreversibility. All natural energy conversions are irreversible, which is to say that energy converted from one form to another cannot then be completely converted back to its original form. As an example, a falling rubber ball has its original amount of gravitational potential energy converted to the kinetic energy of motion. When it strikes the ground, this kinetic energy is converted, by distortions of the molecules within the ball, to elastic potential energy. A large fraction, but not all, of this elastic potential energy is then converted back to kinetic energy when the ball rebounds. No ball (not even the "super ball") bounces all the way back to its original height. We could gain a strong clue as to where this "lost" energy resided if we could take the temperature of the ball before and after its bounce. We would find it warmer afterward: some of the original mechanical energy is converted to heat energy; the "heat tax" is collected.

This "heat tax," of course, is collected in all the energy conversions we showed in Figure 3-1. In conversions to and from mechanical energy, some of the heat tax is paid through the dissipative force, friction. In thermal conversions, some of the heat leaks out of the system. In electrical conversions, some of it is changed to heat by the electrical resistance and leaks away. The heat tax is also paid in energy storage conversions. When water is pumped uphill, for instance, some of the initial energy is lost again to friction in the pump, in the water, and between the water and the pipe.

In all the conversions we have been considering, therefore, there are "losses"; energy is diverted from its intended use. A measure of the importance of these losses is the efficiency of an energy conversion device.

Efficiency

An efficient person is one who seems to get a lot of work done with a minimal expenditure of effort. The physical definition of efficiency is similar; the efficiency of any energy conversion is the ratio of the useful work or energy that is derived from the conversion, to the work or energy put into it. In symbols, the efficiency E is

$$E = \frac{\text{Work or Energy Out}}{\text{Work or Energy In}} \times 100$$

(The multiplication by 100 allows us to express the efficiency as a percent.)

As an example, if we burn a gallon of gasoline in an automobile engine set on a test block and measure the mechanical work output, we find that it amounts to 8,200 Calories. The chemical potential energy of the gallon of gasoline is 32,830 Calories. The efficiency of the engine, therefore, is

$$E = \frac{8{,}200 \text{ Calories} \times 100}{32{,}830 \text{ Calories}} = 25 \text{ percent}$$

The efficiencies of other energy conversions are defined in like manner. Although it is theoretically possible to convert all of a given amount of chemical potential energy to heat by combustion, furnaces are not 100 percent efficient, some of the fuel is not completely burned and some of the heat energy is lost through the furnace walls. The efficiency of a conversion to heat energy is, therefore,

$$E = \frac{\text{Heat Delivered}}{\text{Chemical Energy Input}} \times 100$$

These two examples are of conversions to kinetic forms. In the conversions of kinetic to potential energy, the storage conversions, the efficiency, again, always falls below 100 percent. The "heat tax" is imposed. In the "pumped storage" generating plants, which are described in Chapter 6, surplus electric power is used to pump water uphill. When more power is needed, that water is allowed to flow back through the turbine and to generate electricity. It is found that if 3 kw-hr of electric energy is used to pump the water, 2 kw-hr are produced when the water runs back through the turbines. The efficiency, therefore, is

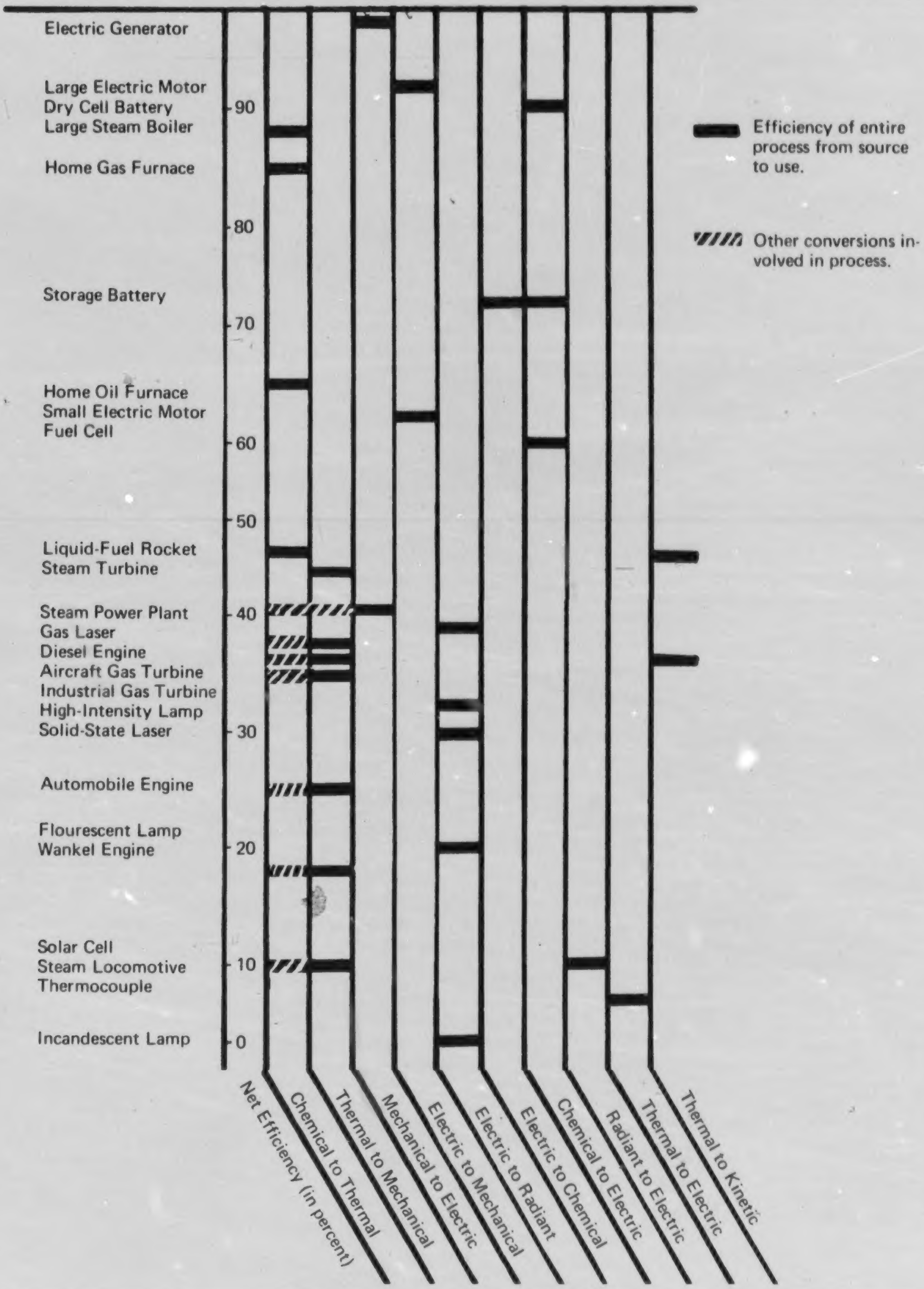
$$E = \frac{2 \text{ kw-hr (output)}}{3 \text{ kw-hr (input)}} \times 100 = 67 \text{ percent}$$

We have gathered together in Figure 3-8 data on the efficiencies of most of the important energy conversion processes. The conversions to and from electric energy stand at the top of the list; the large generators have efficiencies of near 100 percent (but *not* 100 percent). Next in line are the conversions from chemical energy to thermal (heat) energy. The heat engines, which as we have said are involved in half of our industrial energy conversions, all have efficiencies that are less than 50 percent. The automobile engine, both the conventional internal combustion engine and the Wankel (rotary) engine, are 25 percent efficient, or less. Further down the list are, for instance, the solar cell, which converts light energy to electrical energy, and the lightbulb, which accomplishes the reverse conversion.

If we now look back at the data on energy consumption in the preceding section, we begin to see the signs of waste and inefficiency in our system. One-quarter of

153

FIGURE 3-8
Efficiencies of Important Energy Conversion Processes



Adapted from **Energy and the Future**, Hammond, Metz, Maugh, AAAS, Washington, D.C., 1973, pg. 133.

the total energy is used in the transportation sector where the engines are at best 25 percent efficient. This means that three-quarters of that energy is wasted. Another quarter of the total energy is used in generating electricity, most of this in the fossil-fuel fired plants. They are at best 30 percent efficient; two-thirds of this energy is wasted. The situation is, in fact, worse than this as we shall see when we discuss the concept of "system efficiency." Before we introduce that concept, however, let us look briefly at these heat engines that waste so much energy and see why this happens.

Heat Engines and the "Thermal Bottleneck"

Any device that converts heat energy into mechanical energy is called a heat engine. This is an important class of devices, accounting for about half of our energy conversions. The inefficiency of this conversion is responsible for much of the waste of energy in our system. Unfortunately, it is an inescapable inefficiency; it is guaranteed by the laws of physics.

In Chapter 1 we paraphrased the "Second Law of Thermodynamics" as

> *In any conversion of energy from one form to another some of it becomes unavailable for further use.*

This is an interpretation of the actual law. In its more precise form it would be

> *No device can be constructed, which operating in a cycle (like an engine) accomplishes only the extraction of heat energy from a reservoir and its complete conversion to mechanical energy (work).*

This statement can be read, "You can't build a 100 percent efficient heat engine." In practice, however, the application of this law has an even stronger penalty.

There is much interesting science in the story of what heat energy really is and how it can be transformed into mechanical work, but we won't take the space to tell it here. We do provide some of that story in Technical Appendix 4. We will content ourselves with the highlights and the results here.

The form of energy we call heat energy shows itself as the random, chaotic motion of molecules. As the heat energy increases, as the material gets hotter, the temperature (which is an indicator of "hotness") increases. As we show in Technical Appendix 4, the temperature of a substance depends directly on (is a measure of) the average kinetic energy of the molecules of the hot substance.

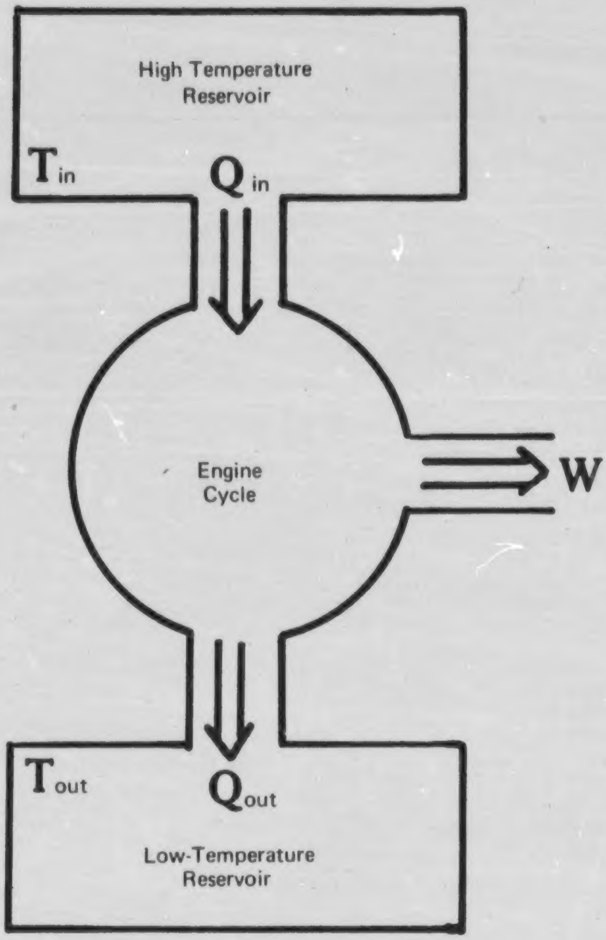
The hot substance in heat engines is usually a gas. In the reference appendix we describe the way in which some of the random motion of the gas molecules can be converted to the mechanical motion of a piston. We will skip those details and look at the process schematically.

For our purposes the important happenings in a heat engine are the following: gas is heated (by combustion within the engine in an internal combustion engine and outside of it in a steam engine), the hot gas drives a piston (does work) and is then exhausted at a lower temperature. This is a cyclic process (it is repeated) and the gas (or steam) is but a carrier for energy. Such a cycle is diagrammed in Figure 3-9. An amount of heat energy, Q_{in}, is removed from a hot reservoir (the furnace-boiler of a steam plant, for instance), an amount of work W is accomplished, and the remaining energy, Q_{out}, is exhausted to a cold reservoir (the outside atmosphere, for instance).

In this diagrammatic form we can think of a heat engine working like a waterwheel. Energy flows from a high-temperature region to a low-temperature region and does work in the process.

The difference in temperature between the gas at the beginning of the working cycle and the end provides a

FIGURE 3-9
Schematic Diagram of a Heat Engine



Legend:
Q_{in} = Input heat energy
Q_{out} = Output heat energy
W = Work produced by engine
T_{in} = Input temperature
T_{out} = Output Temperature

measure of the efficiency of the cycle. The temperature is a measure of the energy contained in the gas. The fact that it is lower at the end of the cycle shows that energy was removed — work was accomplished. The efficiency relation for a heat engine is, in fact:

$$E = \frac{T_{in} - T_{out}}{T_{in}} \times (100)$$

In words, this says that efficiency is the difference between the input and output temperature (which is proportional to the work done) divided by the input temperature (which is proportional to the input energy). This expression can be rewritten in a more useful form (by dividing by T_{in}) as

$$E = 1 - \left(\frac{T_{out}}{T_{in}}\right) \times 100$$

This expression gives the efficiency of a "perfect engine" (one with no losses to friction or leakage) operating between T_{in} and T_{out}. Real engines are even less efficient than this.

Before we go on to apply this, one further explanation is necessary. The temperatures T_{in} and T_{out} must be measured on an "absolute" scale, that is a scale on which zero is taken at the temperature called "absolute zero." As we show in Technical Appendix 4, where absolute temperature is explained, to convert conventional Fahrenheit temperatures to an absolute scale we have to add 460°F, to convert Celsius temperatures to the appropriate absolute scale we add 273°C. In this form we have further evidence that 100 percent efficiency is impossible. There are only two ways that the equation we have just written can give us 100 percent. Either T_{out} is zero or T_{in} is infinite. Both of these temperatures are physically impossible to reach.

Let us make the prediction of the equation more concrete by an example. In a modern steam turbine the steam comes in at 1,000°F and exhaust temperature cannot be less than 212°F (the temperature of boiling water). Thus, its highest possible efficiency is

$$E = 1 - \left(\frac{(212 + 460)}{(1{,}000 + 460)}\right) \times 100$$

$$= (1 - .46) \times 100$$

$$= 54 \text{ percent}$$

Actual turbines reach 40 percent efficiency.

This efficiency equation, in fact, suggests how to increase efficiency. We must either raise T_{in} or lower T_{out}. Unfortunately, steam turbines now work very near the practical limits imposed by the strength of the boilers, pipes, etc. and the projected limits are temperatures of around 1,500°F. The input temperature can't go much higher. We cannot gain much at the other end either, for we cannot take steam below the temperature of boiling water. It may be possible, however, to use fluids (ammonia for example) that boil at lower temperatures and reduce T_{out}. We will discuss some of these "bottoming cycles" in Chapter 6 along with some ideas that may give us a higher T_{in}.

The efficiency of the automobile engine can also be anticipated by the use of this equation. The input temperatures are high, perhaps as high as 4,000°F. The exhaust gas, however, is still very hot (as anyone who has accidentally touched an exhaust pipe knows), on the order of 1,000°F. An upper limit on automobile engine efficiency is, therefore,

$$E = 1 - \frac{(1{,}000 + 460)}{(4{,}000 + 460)} \times 100$$

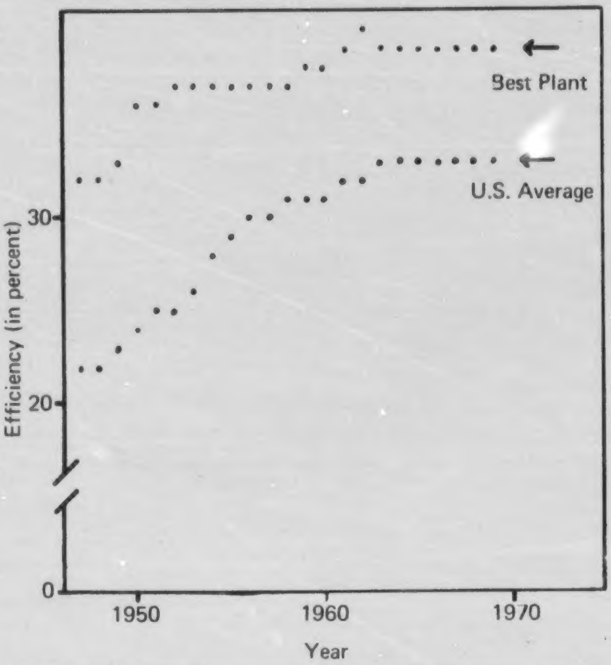
$$= (1 - .33) \times 100$$

$$= 67 \text{ percent}$$

In a real engine, however, much of the heat energy leaks out through the engine and, as we have said, actual efficiencies are less than 25 percent.

These two examples were chosen, of course, because of the importance of the turbine and the automobile engine. For this reason it is of interest to examine the historic trend of efficiency. In Figure 3-10 we plot the generation of electricity over the past few decades. This efficiency includes the efficiency of the generator, the boiler, etc. as well as the turbine; but as we have seen in Figure 3-8, these other efficiencies are quite high. What we see from Figure 3-10 is great improvement over the past decades, but a flattening out

FIGURE 3-10
Efficiency of Electric Generation, 1947 to 1969

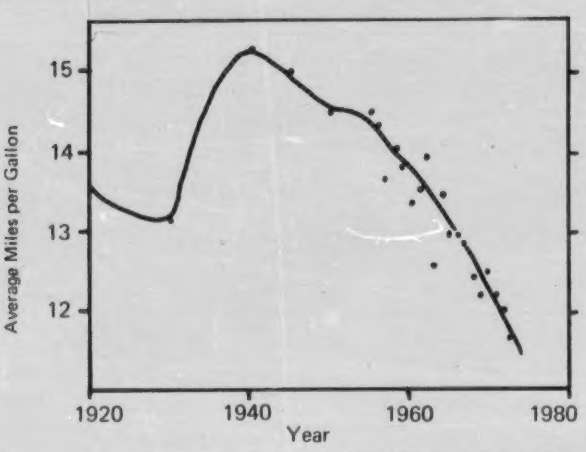


that tells us not to expect much further improvement. We are approaching the limiting value given by our efficiency equation.

Figure 3-11 shows the historic record of the efficiency of automobile engines. What is plotted is miles per gallon, but since miles are the desired output and gallons the input this can be read as a plot of efficiency. Figure 3-11 is disturbing in that it does not show improvement, except that recorded in the 1940s when leaded gas and high-compression engines were introduced. The efficiency has, in fact, decreased over the past decade or so. The causes of this unhappy trend are several; cars have gotten heavier, more complex (automatic transmission, power brakes, etc.), and air conditioning, stereo, and other life-support systems have been added. There has been much recent criticism of the miles-per-gallon penalty of the emission control systems. We will comment on this later. We can, if we like, view the data of Figure 3-11 as good news. There is room for improvement here.

We will add one further note about heat engines. We see from the efficiency equation that heat energy at a high temperature has extractable energy in it. When we let it degrade to low temperature without obtaining work from it, we are wasting potential. In a home furnace, for instance, the temperature may be as high as 7,000°F and this is degraded to the 70°F or so of a comfortable room. The amount of heat energy is still the same, a much larger volume of gas has been heated, but the potential of doing work has been lost. The electrical resistance heater with its high-temperature wires suffers the same defect. A more efficient way to heat a room was first described in the 19th century. It works on the principle of a refrigerator.

FIGURE 3-11
Efficiency of Automobiles

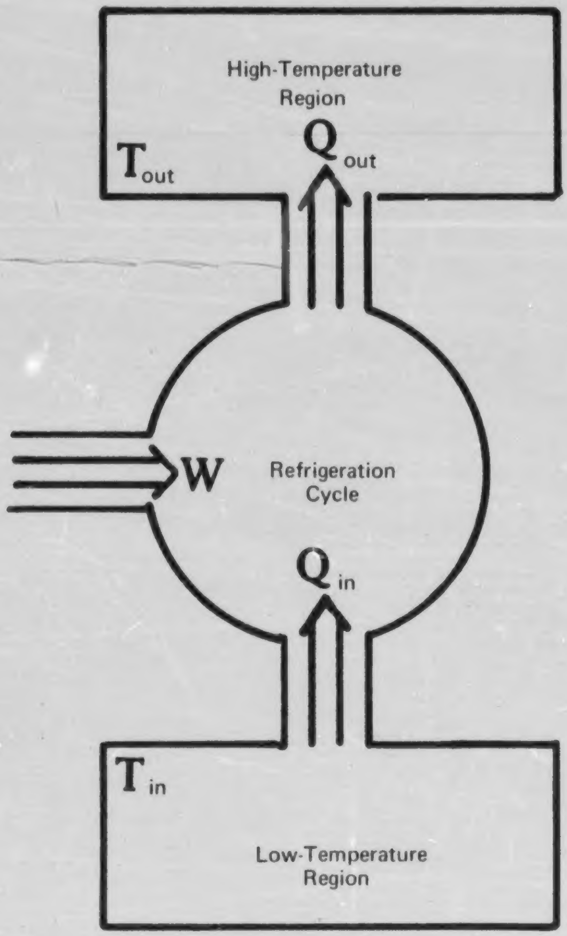


Data from
1940-56 – **Energy in the American Economy**, Schurr and Netschert, Maryland: The Johns Hopkins Press, Baltimore, 1966.
1957-73 – **A Report on Automotive Fuel Economy**, U.S. Environmental Protection Agency, Washington, D.C., 1974.

Heat Pumps, Heat Engines in Reverse

The heat engine that we showed schematically in Figure 3-9 can be turned around and used, as we show in Figure 3-12, to pump heat from a cold region into a hotter one. This is the principle of the refrigerator. Work, W (electric energy in most refrigerators), is used to extract heat energy, Q_{in}, from a cold region and pump it to a hotter one. We won't go into the operating details of a refrigerator other than to say that a condensed gas is put into contact with the interior, it expands and absorbs heat energy and is then pumped outside, compressed (which raises its temperature) and it then gets rid of this excess heat energy since it is now hotter than its surroundings. The cycle is then repeated. The work goes

FIGURE 3-12
Schematic Diagram of a Heat Pump



Legend:
Q_{in} = Input heat energy
Q_{out} = Output heat energy
W = Work required to transfer heat energy
T_{in} = Input temperature
T_{out} = Output temperature

into pumping the gas around the system and compressing it. Anyone who has investigated a refrigerator at all, or has been near one in the summer, is aware that it gives off heat.

Air-conditioners work on the same general principle; they, as refrigerators, "pump heat" from the cooler region to the warmer one. In both these appliances the heat is an unwanted by-product. It need not be so. The home "heat pump," which is used in several hundred thousand houses (mostly in the regions of moderate climate) in this country, works like an air conditioner in reverse; it cools the outdoors and pumps heat indoors. These devices are, in fact, reversible and can be used to cool the indoors in the summer.

Why they are more efficient than the electric resistance heater can be made clear with a simple example. In a resistance heater a kilowatt is converted into a certain number of Calories (860 to be exact). In a heat pump this same kilowatt can be used to run the motors and compressors and to pump two or three times that number of Calories from the outside in. What is accomplished by a "heat pump" (of a refrigerator) is to move a certain amount of heat through a relatively small temperature difference. This is similar to the options you might have if you had a reservoir on a hilltop over your garden. You could let the water run down and irrigate your garden. You could get much more water to your garden if you used the energy of the water to turn a water wheel that pumped water to the garden from a pond lying slightly below the garden. Heat pumps are similarly more efficient when they pump heat through a relatively small temperature difference. It may be that the increasing cost of electric energy will cause us to turn to this more efficient device.

System Efficiencies

In this chapter we have dealt with the pattern of consumption and with the efficiency of individual energy conversion processes. Now it is useful to bring these ideas together with the concept of *system efficiency*. In this approach we look at the end use (home heating, for instance), at the primary source (which could be petroleum), and at all the steps along the way. At each of the conversions a "heat tax" must be paid, some of the energy is lost as far as further use is concerned. To make meaningful comparisons between alternate energy forms and to be able to assess the real energy cost, for instance, of automobile transportation, it is useful to know the efficiency with which the energy of the fossil fuel in the ground is used for its intended purpose.

We collect, in Tables 3-16 to 3-19, the system efficiencies of electric lighting, of space and water heating by electricity or fossil fuels, and of automobile transportation. In all these examples of overall processes, very little of the energy we begin with ends up delivered to the intended use. The comparison between space heating by electricity and by the fossil fuels is particularly revealing. We will consider the implications of this further in the chapter on energy conservation.

With these system efficiencies in mind we can now profitably consider the United States energy flow from a system efficiency point of view. A schematic diagram of

TABLE 3-16

Energy System Efficiency of Electric Lighting (from coal-fired generation)

Step	Efficiency of Step (in percent)	Cumulative Efficiency (in percent)
Production of Coal	96	96
Transportation of Coal	97	93
Generation of Electricity	33	31
Transmission of Electricity	85	26
Lighting, Incandescent (fluorescent)	5 (20)	1.3 (5.2)

TABLE 3-17

Energy System Efficiency of Water Heating

Step	Efficiency of Step (in percent)	Cummulative Efficiency (in percent)
Electric (coal-fired)		
Production of Coal	96	96
Transportation of Coal	97	93
Generation of Electricity	33	31
Transmission of Electricity	85	26
Heating Efficiency	92	24
Natural Gas		
Production of Natural Gas	96	96
Transportation of Natural Gas	97	93
Heating Efficiency	64	60

TABLE 3-18

Energy System Efficiency for Space Heating

Step	Efficiency of Step (in percent)	Cumulative Efficiency (in percent)
Electric (coal-fired)		
Production of Coal	96	96
Transportation of Coal	97	93
Generation of Electricity	33	31
Transmission of Electricity	85	26
Heater Efficiency	95	25
Fuel Oil		
Production of Crude Oil	96	96
Refining of Fuel Oil	90	86
Transportation of Fuel Oil	97	84
Furnace Efficiency	63	53
Natural Gas		
Production of Natural Gas	96	96
Transportation of Natural Gas	97	93
Furnace Efficiency	75	70

this is provided by Figure 3-13. We see that in 1971 14.2 Q Calories worth of energy were extracted from domestic primary sources, 2.2 Q Calories of energy were imported (petroleum and natural gas), and 0.4 Q Calories exported (metallurgical grade coal).

Of the 3.9 Q Calories that went for the generation of electricity, 2.5 Q Calories, two-thirds of it, were wasted.

TABLE 3-19

Energy System Efficiency of the Automobile

Step	Efficiency of Step (in percent)	Cummulative Efficiency (in percent)
Production of Crude Oil	96[a]	96
Refining of Gasoline	87[a]	84
Transportation of Gasoline	97[a]	81
Thermal to Mechanical-Engine	[b]25-30[c]	20-24
Mechanical Efficiency-Transmission (includes auxiliary systems)	50-60[c]	10-15
Rolling Efficiency	60[c]	6-9

[a] **Energy Sources, The Wealth of the World**, E. Ayres, C. Scarlott (New York: McGraw-Hill) 1952.

[b] "The Conversion of Energy," Claude Summers, **Scientific American 224**, #3, p. 153, 1971.

[c] "The Energy Outlook for Transportation in the U.S.," M. E. Campell, **American Highways, 52**, #3, p. 25, 1973.

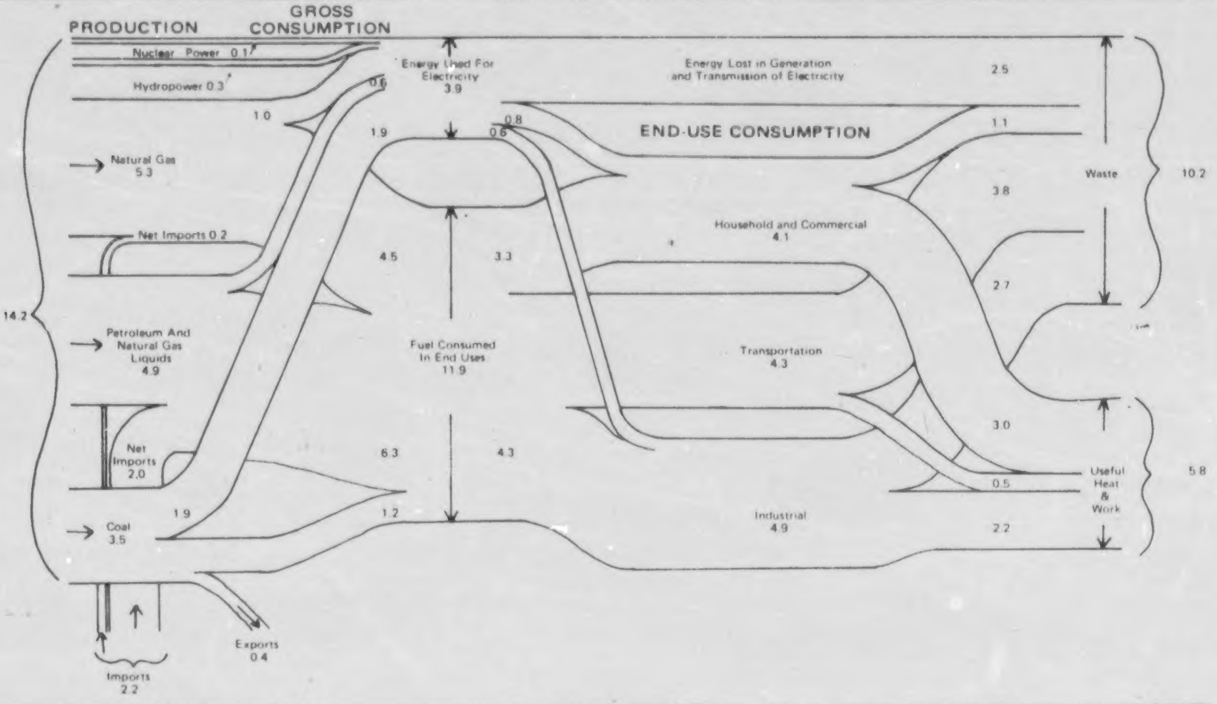
Of the 4.1 Q Calories used in the household and commercial sector, 1.1 Q Calories were wasted as were 3.8 Q Calories, almost 90 percent, of the 4.3 Q Calories used in transportation. In the industrial sector, 2.7 Q Calories of the 4.9 Q Calories input were wasted. Overall, of the 16.0 Q Calories input to the system, 10.2 Q Calories were wasted and only 5.8 Q Calories actually produced the end use work or heat. The overall efficiency of the system, therefore, was 36 percent; a little less than two-thirds of the energy is lost as far as the intended purpose is concerned. The future prognosis, as far as this efficiency is concerned, is not bright. Electric energy consumption and transportation, the two most wasteful sectors, are rapidly growing sectors. We will look again at this energy flow diagram when we consider strategies for energy conservation.

The One-way Street

We have followed energy in this chapter from the primary sources — coal mines and wells for oil and gas — to the end uses. It has been a trip down a one-way street. At each conversion of energy along the route, some of it has gone into waste heat. This waste heat is discharged into the atmosphere or into our rivers and lakes by the electric utility plants, it is given off by the wires that carry electricity, lost from our poorly insulated houses and commercial buildings, lost by inefficient furnaces and, in great quantities, lost to the atmosphere by the inefficient engines of our automobiles.

FIGURE 3-13

Approximate Flow of Energy Through the United States Economy, 1971, in Q(10^{15}) Calories


PRODUCTION
GROSS CONSUMPTION
Nuclear Power 0.1
Hydropower 0.3
1.0
0.6
Energy Used For Electricity 3.9
1.9
0.8
0.6
Natural Gas 5.3
Net Imports 0.2
4.5
3.3
14.2
Petroleum And Natural Gas Liquids 4.9
Fuel Consumed In End Uses 11.9
Net Imports 2.0
6.3
4.3
1.9
1.2
Coal 3.5
Exports 0.4
Imports 2.2
Energy Lost in Generation and Transmission of Electricity
2.5
END-USE CONSUMPTION
1.1
3.8
Household and Commercial 4.1
2.7
Transportation 4.3
3.0
0.5
Industrial 4.9
2.2
Waste
10.2
Useful Heat & Work
5.8

Source: Earle Cook, Texas A&M University

Heat is also the end product of all the conversions. The electric energy that is produced and delivered to homes and industry is eventually converted to heat directly (in baseboard heaters, toasters, and ranges) or indirectly (by the friction in electric motors, for instance). The kinetic energy of the moving cars, trucks, etc. of our transportation system is converted to heat by brakes, air resistance, and other dissipative forces.

In the end, all the primary forms of energy converted to our use end up in the form of heat. Furthermore, it quickly becomes low-temperature heat in the air and water, and, as we see from our efficiency equation,

$$E = 1 - \frac{T_{\text{out}}}{T_{\text{in}}} \times 100$$

it is of little further use to us. Since T_{in} is now the ambient temperature, the average temperature of the surroundings, it is not possible to use it efficiently in some further engine (T_{in} is about the same as T_{out} and E is, therefore, about zero). What happens to it was shown back in Figure 1-1; it is reradiated out from earth into the vast reaches of space. We are warming up the universe.

The one-way nature of the conversion to heat energy is a consequence of the Second Law of Thermodynamics which we discussed in the section on efficiency. We are stuck with the heat tax; it can't be repealed. The only direction in which we can move with profit, therefore, is toward processes that don't involve heat energy as an intermediate form; that is, away from heat engines. We need conversion techniques to go from chemical or thermal energy directly to electric energy. We will discuss some of these possibilities in the chapter on energy technology. For the immediate future, however, we will continue to send most of our energy through the thermal bottleneck and must be content with trying to plug up some of the leaks.

Summary

In this chapter we looked in detail at the flow of energy through our society. We examine the amount of energy that goes into the various consuming sectors and at the efficiency with which it is converted.

In 1968 a total of 15.3 Q Calories of energy was consumed in this country. (The total in 1974 was 18.5 Q Calories.) Of the 1968 total, 41 percent was consumed by industry, 25 percent by transportation, 19 percent in the residential sector, and 15 percent in the commercial sector. (These percentages remain about the same.) The major end use was heat, for space heating and for the various heat-driven industrial processes. More than half the total energy was used for heat, an additional third was used as mechanical energy.

If the production of electric energy were treated as a separate consuming sector, it would account for a little more than a quarter of the total primary energy in 1973. This electricity was, in turn, consumed in only three sectors; 45 percent in industry, 31 percent in the residential sector, and 24 percent in the commercial sector in 1968.

The Second Law of Thermodynamics assures that all energy conversions are less than 100 percent efficient. Among those that are important in our economy are the steam turbine, 40 percent efficient at best, and the automobile engine, which converts heat to mechanical work with an efficiency of about 25 percent. As we pointed out, a more important measure than the efficiency of a single conversion device is the system efficiency, the cumulative efficiency of a process from the extraction of the fuel to the final delivery of the desired energy product. We displayed these system efficiencies: electric lighting, 1 percent efficient (5 percent for fluorescent lights); water heating, 24 percent efficient with electricity and 60 percent efficient with gas; space heating, 25 percent efficient with electricity, 53 percent efficient with fuel oil, and 70 percent efficient with natural gas. The final one, automobile transportation, is 6 to 9 percent efficient as a system.

Taking this point of view, we look at the United States system and find an approximate 36 percent overall efficiency.

The major offender, when we look at these efficiencies, is the heat engine. About half of our energy flows through the "thermal bottleneck," the conversion of thermal energy to mechanical energy. The Second Law of Thermodynamics assures us that much of the input energy to this process will become unavailable as low-temperature heat energy.

In the end, of course, all our primary energy ends up, after many conversions, as heat and is radiated away to imperceptibly warm the universe. This is the real energy crisis and it is unavoidable.

CHAPTER 4

The Exponential Century

The Exponential Century

A large percentage of the problems of the 1970s are problems of growth; we have suddenly become too many and the world and its resources have become too small. We have too many cars and too much highway, we need too much food and too many houses, etc. Not surprisingly, a large part of the crisis in energy and the environment can also be traced to growth, an aspect we will examine in this chapter. We will enter the hazy area of projection and prediction and try to assess the amount and the form of energy this country, and the world, will require for the remainder of the century. And since the past is often (but not always) a key to the future, we will also examine the historical record of growth in overall energy consumption and in production and consumption of the individual energy forms.

We can state much of the facts of growth pictorially. In Figure 4-1, two curves are shown, the growth of population and of energy consumption in this country. Figure 4-2 shows similar world data.

Plotted linearly these figures dramatize the growth. The Figures 4-1 and 4-2 curves, especially the energy curves, rise sharply during the 70 years of this century. To make a point about the relationship of energy consumption and population growth, we have started both curves from the same point (by shifting the axis of the energy curve). What becomes clear from this presentation is that energy consumption is growing more rapidly than population, and, therefore, that *per capita* consumption is growing. Population growth accounts for only a small percentage of total growth.

Semilog Plots and Doubling Times — An Aside

When dealing with growth, in particular with the rapid growth we see here, it is much easier to study it if we plot the data in a "semilogarithmic" graph. We discuss the "semilog" plots, and the "exponential curves" for which they prove so useful, in some detail in Technical Appendix 2. We will briefly summarize that discussion here.

Whenever a quantity grows at a constant annual rate of increase, like compound interest, for instance, it increases in a manner called exponential. The world energy consumption or the population growth of Figure 4-2, if smoothed out, would be good examples of this type of growth. If such an exponential curve is plotted on a semilogarithmic graph, one in which the vertical axis represents the logarithms of the numbers rather than the numbers themselves, the exponential curve becomes a straight line. We replot the data of Figures 4-1 and 4-2 in this way as Figures 4-3 and 4-4.

Reading semilog graphs: Reading these semilog graphs is not as difficult as it may appear at first. It is the graph paper on which the numbers are plotted that has to worry about logarithms. What we plot, and what you read, are the numbers themselves. Thus on Figure 4-3, to find out what the United States population was in 1950, you look to the point at which the vertical line from 1950 crosses the curve and then travel horizontally from this intercept to the right-hand population scale and read the number, which is about 151 million.

Doubling times and rates of growth: These semilog presentations have long regions in which the data can be fairly well represented by a straight line. During these periods, therefore, the growth was exponential. United States energy consumption from 1850-1895 and from 1935-1973 are two examples. (The exponential growth of energy consumption in both examples was broken by the depression of the 1930s.) The usefulness of this straight-line relationship is in the ease with which the *doubling time* can be read from it. A definitive characteristic of exponential growth of a quantity is that it doubles at a constant rate. Thus energy consumption in the United States, 10.0 quadrillion (Q) Calories in 1954, will reach 20 Q Calories (the extended straight line) in 1974. The doubling time is 20 years. Similarly, the doubling time for population over the same period can be found from the graph to be 45 years (1922-1967), and energy consumption doubled every 27 years in the latter half of the 19th century.

Another useful quantity, the *annual rate of growth* (the percentage by which the quantity increases each year), is related to the doubling time and can also be easily found for the straight-line portions of these curves. The relation, where r is the rate of growth in percent per year, is

$$r = \frac{70}{\text{doubling time (in years)}}$$

Thus the annual rate of growth of United States energy consumption since about 1935 has been $r = 70 \div 20$, or 3.5 percent per year. Population over that same period increased at $r = 70 \div 45$, or 1.56 percent per year. We will leave it to the reader (or the students) to compute from Figures 4-3 and 4-4 other doubling times and annual rates.

The Historical Record—the Fuels

With the previous exercise as preparation, we will look now at the historical record of both the production and consumption ends of the energy flow pattern. The record shows growth and change. A new fuel is found, new uses are invented that increase the demand, and, finally, the demand stimulates the invention or discovery of new fuels. This interplay is displayed for the important primary energy sources in Figure 4-5, which shows the percentage of total energy supplied by each during the past hundred or so years.

Figure 4-5 shows three cycles of change: wood dominated the latter half of the 19th century; coal was the favored fuel in the first half of the 20th century and the petroleum products have now taken over. In the decade of the 1970s we may see the beginning of a fourth cycle — nuclear energy, 1 percent of the total in 1970, is expected to provide 40 percent of the total by 2000. Water power (hydro) has remained around 5 percent.

What must be remembered, of course, is that even though the percentage contribution of a certain fuel may decline, the absolute amount consumed is growing. We see this clearly in the data on energy production from the individual sources which follow.

FIGURE 4-1
Historical Record of U.S. Population Growth and Energy Consumption

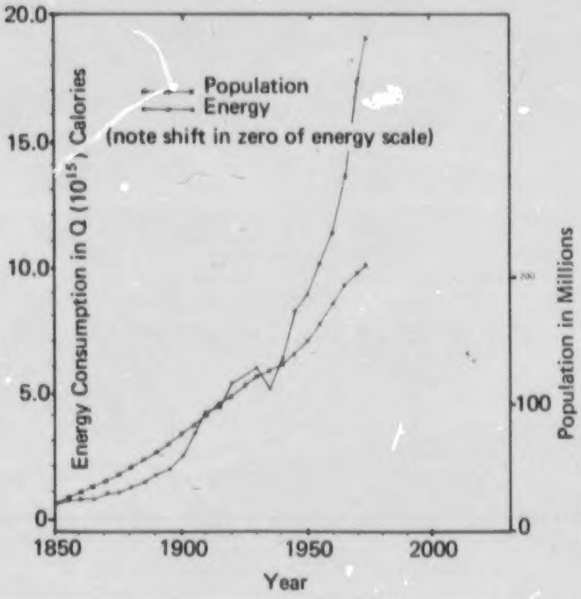


FIGURE 4-2
Historical Record of World Population Growth and Energy Consumption

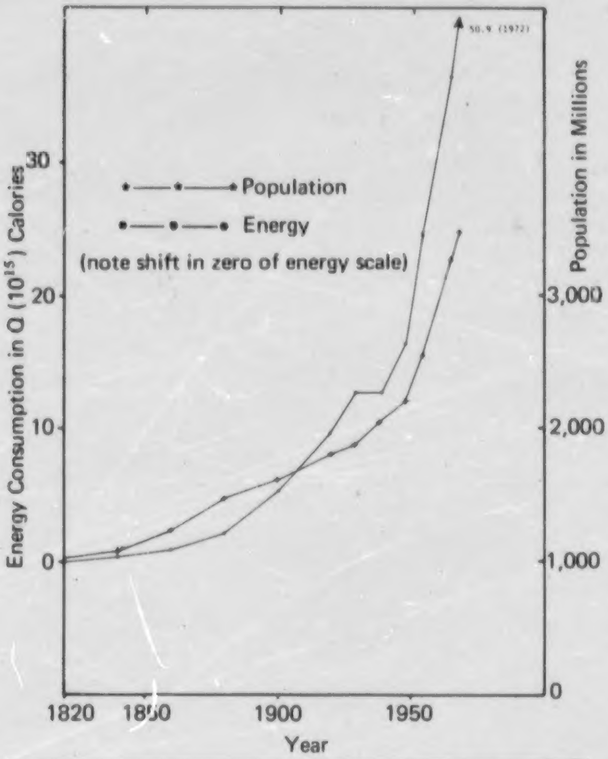


FIGURE 4-3
U.S. Energy Consumption and Population – Semilog Plot

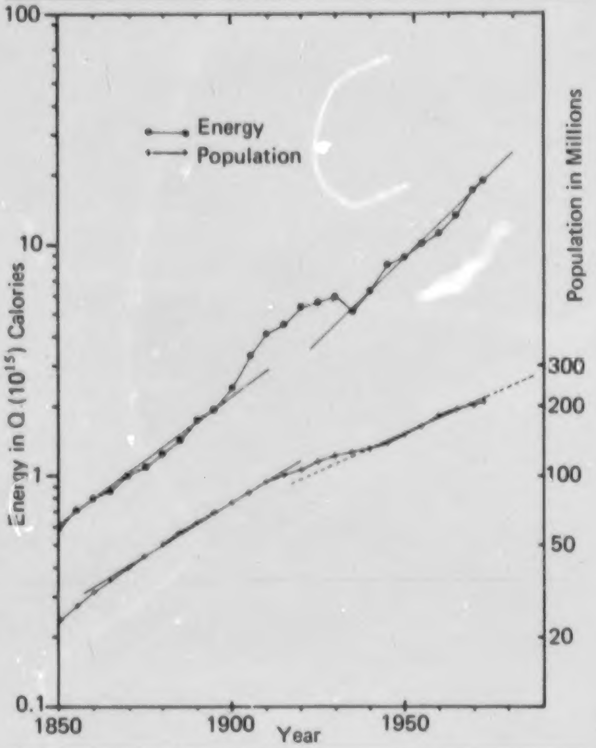
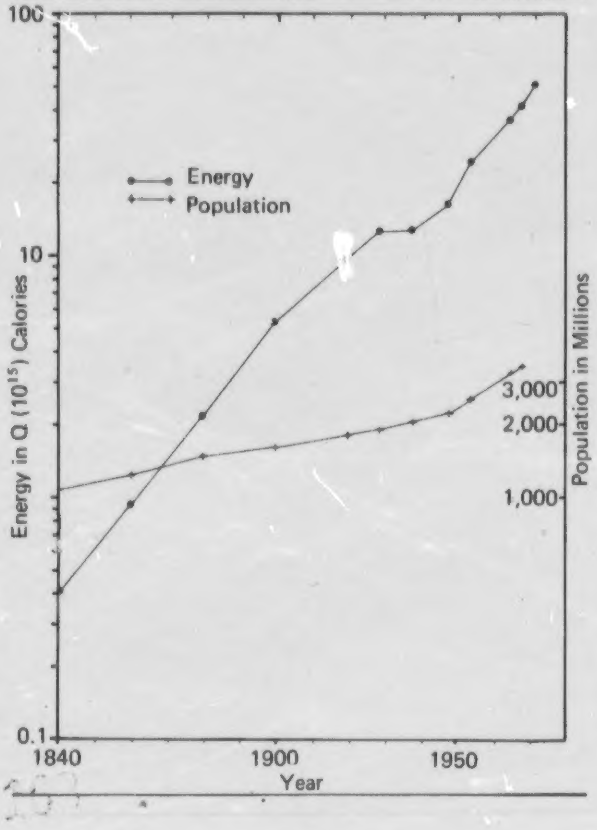


FIGURE 4-4
World Energy Consumption and Population – Semilog Plot



Wood

The record of fuel wood consumption in this country is shown in Figure 4-6. A favored fuel in this forested country for a hundred years or so, consumption reached a peak of almost 140 million cords in 1870 and has steadily declined since then. (A cord of wood is a stack of wood 4 feet by 4 feet by 8 feet that produces roughly 5 million (M) Calories of energy.)

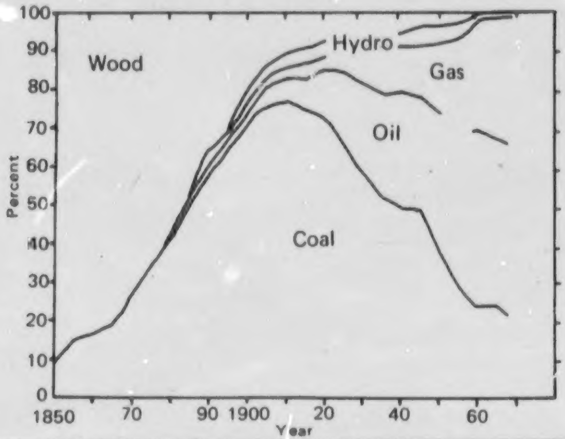
Much of this wood was used in home heating, an estimated 17.5 cords per house per year in 1850-1860, and by the end of the century wood had also begun to play an important role in industry and transportation. Although wood is no longer an important fuel as far as its percentage contribution is concerned, large amounts are still burned. We see from Figure 4-6 that only twice as much wood was burned in 1850 as in 1950. In 1950 it still contributed 10 percent of the residential energy and an estimated 70 percent of rural heat.

Coal

The first of the great replacement cycles featured coal. Although used extensively for fuel in Europe in the 18th and 19th centuries, the European immigrants to this country turned to coal only after the great forests had been chopped down. Coal, plentiful in the Eastern Appalachians near the developing industries, has a higher energy density than wood (more Calories per pound) and is thus the preferred fuel if it has to be transported. The demand for coal was fed by changes in the industrial and transportation sectors; the steel industry used coke, a coal-derived fuel, and the growing railways had coal-fired steam engines.

The historical record of coal consumption in this country is given in Figure 4-7. Coal use has gone through its own cycles. It peaked in 1920 at 660 M tons, then began to fall as oil cut into the heating market. It peaked again during the petroleum-short period of World War II, then dropped swiftly as the diesel engine began to replace the coal-fired steam locomotive. The rapidly increasing demand for electricity has brought about a third period of growth, since coal provides about half the energy for electricity generation. Demand will also be fed by plants that turn coal into gaseous and liquid fuels. Coal's projected tonnage consumption will go well beyond the 1920 peak. At present our most abundant energy resource, coal is also responsible, in its combustion with present techniques, for a large share of the environmental problems and health hazards of energy production. We will have more to say about coal.

FIGURE 4-5
The Changing Fuel Mix



Oil

Petroleum, also, is a fuel of antiquity. The "Greek Fire" of the Roman sieges was burning asphalt, and an oil well dug in 1640 outside of Modena, Italy, flowed for 200 years providing, among other uses, kerosene for street lighting. The first United States oil well, a well only 69.5 feet deep, was drilled in August 1859 outside of Titusville, Pennsylvania.

The growth of oil production and consumption is shown in Figure 4-8. We see again the almost straight-line growth of an exponential with a doubling time of about 10 years in the early part of this century and 20-25 years at present. The United States was an oil exporting nation until the 1950s but, as we have recently learned to our dismay, has increasingly become an importing one. We imported 36 percent of our petroleum supplies (crude oil plus refined products) in 1973. In 1974 our crude oil imports rose, from 1.18 B bbls to 1.27 B bbls, and made up 37 percent of the total petroleum supply.

The interaction of growth and change is particularly obvious in the pattern of oil consumption. The enormous supply of this cheap fuel led to the development of a variety of uses; kerosene for lamps, heavier oils for heating, and oils and greases for lubricating. The invention of the gasoline engine, in about 1880, produced the present dominant market. Gasoline and fuel oil account for almost 90 percent of the market and their production in the refinery creates the sort of inflexibility we saw in winter 1973 and 1974. If fuel oil is short in the winter, the refineries produce more of it — at the expense of gasoline for the automobile driver in the spring.

Oil replaced coal in heating and as the energy source for railroad transportation. Coal dropped from 75 percent of the total in 1910 to less than 30 percent by 1955, while petroleum grew over this same period from 10 percent to 65 percent. Petroleum products accounted for 77 percent of our energy in 1974. Within the petroleum boom, however, a mini-cycle was taking place with the growing popularity of the "Mr. Clean" of fuels — natural gas.

Natural Gas

Natural gas has increased its share of the energy market from 5 percent in 1925 to 30.4 percent in 1974. It is also an old fuel, used by ancient civilizations in China and Egypt.

The early history of natural gas in this country was one of conspicuous waste. It is estimated that 90 percent of this fuel produced in the rich fields of Oklahoma, Texas, and California was burned at the well or lost in other ways. When the problems of transporting and storing this fuel were overcome, however, its cleanliness and the simplicity of gas furnaces made it increasingly popular.

The growth of demand for natural gas is shown in Figure 4-9. This is almost pure exponential growth with a doubling time of 8 to 10 years. It is a preferred fuel not only from the point of view of cleanliness and simplicity, but, as we have seen in Tables 3-17 and 3-18, from an efficiency viewpoint, also. And it is also more economical to ship than electricity. The fuel cell, which we shall study later, may open up a new market of on-site electric power production. The future of natural gas, however, depends on its availability, and that is in question.

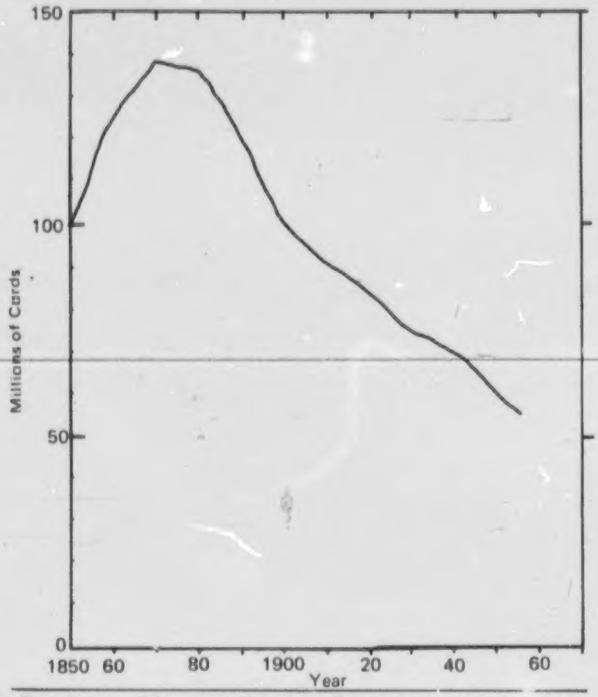
Hydropower and Other Sources

In its energy use, the United States was still in ecological balance in the late 19th century. Most energy was consumed in the home, with wood (secondhand solar energy) the major source. Growing United States industry was also built on secondhand solar sources; wood, wind, and water. In 1850 the sailing ship was of major importance in ocean travel and waterwheels, mostly along New England's streams, were the "prime movers" of industry. In 1850, for instance, wind and water provided 64 percent of the mechanical work for this country, coal, 19 percent, and wood, 17 percent. By 1870 these percentages had turned around. They were: wind and water, 33 percent; coal, 58 percent; and wood, 9 percent. Also important in mid-19th-century America was a different kind of solar "engine," farm animals (primarily horses and mules). Their total horsepower contribution in 1850 was greater than all others and was still equal to them by 1870. By 1900 their contribution had declined to 23 percent, but the number of animals, even in 1920, was still about the same as in 1900 (an estimated 25 million) and one-quarter of the total acres devoted to agriculture was required to feed them.

It is tempting to bemoan the conversion we see in these statistics: from a nation that lived in balance with nature, on the interest so to speak, to a nation drawing on its nonrenewable fossil fuel capital. It is well to look again at Figure 3-6, at our per capita energy use. In 1850 per capita consumption was 25.6 M Calories, with wood, used very inefficiently and mostly for space heating, contributing 23.2 million (M) of these Calories. In 1973, on the other hand, per capita energy consumption was 90.4 M Calories with only 15.4 M of those Calories used in the much more extensive space heating in existence. As environmentally satisfying as that balance with nature appears, we could not have built our present standard of living on it.

While some of the old sources of energy, as we shall see in a later chapter, may come back into limited popularity (energy from wood and other organic waste or new sophisticated windmills, for instance), water power has

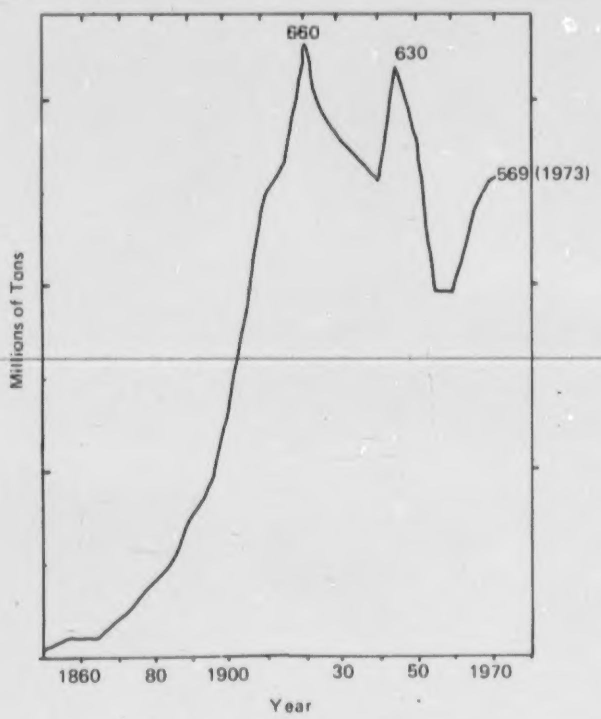
FIGURE 4-6
Consumption of Fuel Wood



Data from Schurr and Netschert, **Energy in the American Economy, 1850-1975.** Baltimore: The Johns Hopkins Press, 1960.

(a) A cord is a stack of wood 4'X4'X8'. It contains approximately 5 million Calories.

FIGURE 4-7
Consumption of Coal

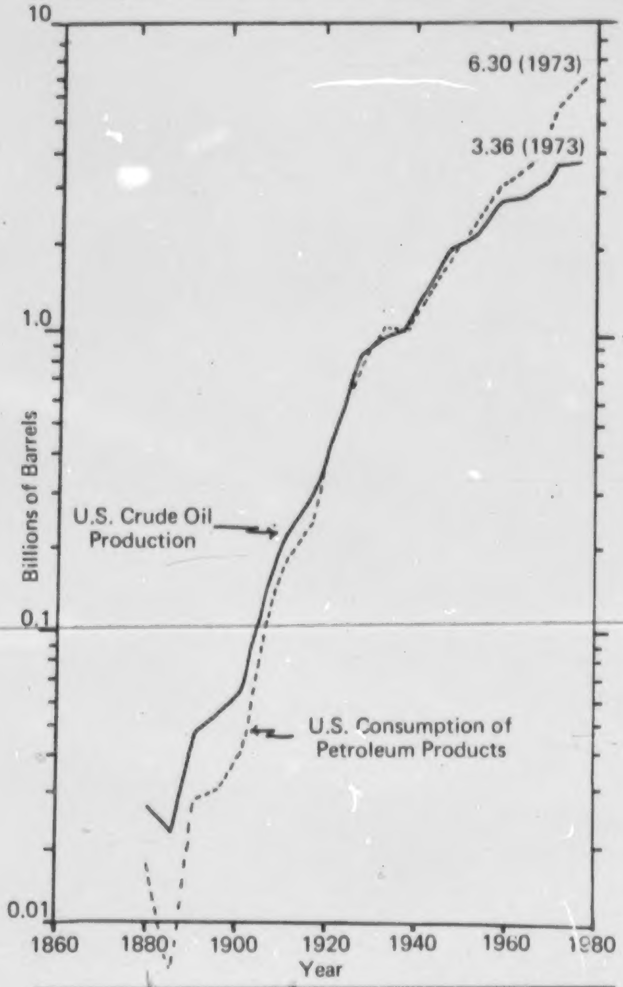


Data from Schurr and Netschert, **Energy in the American Economy, 1850-1975.** Baltimore: The Johns Hopkins Press, 1960.

continued to be of steady, if minor, importance. The first electric generator, at the Pearl Street Station in New York City in 1882, was a coal-fueled steam engine. The second one, in operation a few months later on the Fox River near Appleton, Wisconsin, was water powered. It is in the generation of electricity that water power has found its continuing role, and it is presently responsible for about 15 percent of the total generating capacity of the United States.

We plot, in Figure 4-10, the annual total of kilowatt-hours produced by hydroelectric power in this country from that beginning station to the present era of huge dams and reservoirs. The growth has the exponential shape. The total hydro-generated electric energy has been doubling every 16 years during the last few decades. As we saw in Chapter 2, however, the potential for further expansion is limited and we should see a permanent turnover of this curve in the next decade or two.

FIGURE 4-8
U.S. Production and Consumption of Petroleum



Data from Schurr and Netschert, **Energy in the American Economy, 1850-1975.** Baltimore: The Johns Hopkins Press, 1960,
and: Bureau of Mines, U.S. Department of the Interior.

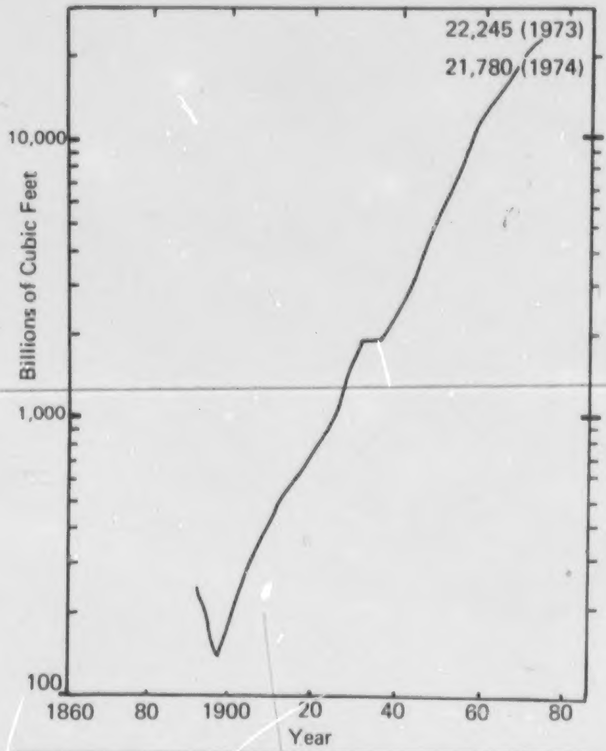
The Historical Record—Consumption

In Chapter 3 we gave a detailed breakdown of the pattern of energy consumption as of the last careful tally (1968). This pattern has undergone growth and change similar to that which occurred in the fuel mix. In Figures 4-1 and 4-3, we showed the historical record of United States consumption. We will look briefly now at the changes in importance that have occurred in the four consumption categories. In the late 19th century, the domestic sector utilized 90 percent or more of the total energy. Table 4-1 summarizes the data for selected years since 1950. We see the expected growth in consumption in all categories, with the household and commercial sectors growing more rapidly than the industrial sector (whose percentages share steadily decreases until the slight increase in 1974). The percentage used by transportation fluctuates near 30 percent.

Electric Energy

In Table 4-1 the kilowatts of electric energy used in each sector are converted to Calories (by multiplying by 860 Calories per kw-hr) and added to the appropriate totals. The subtotal for each year, therefore, is less than the total primary energy used because of the loss of energy in the generation of electricity. In order to provide

FIGURE 4-9
U.S. Natural Gas Consumption



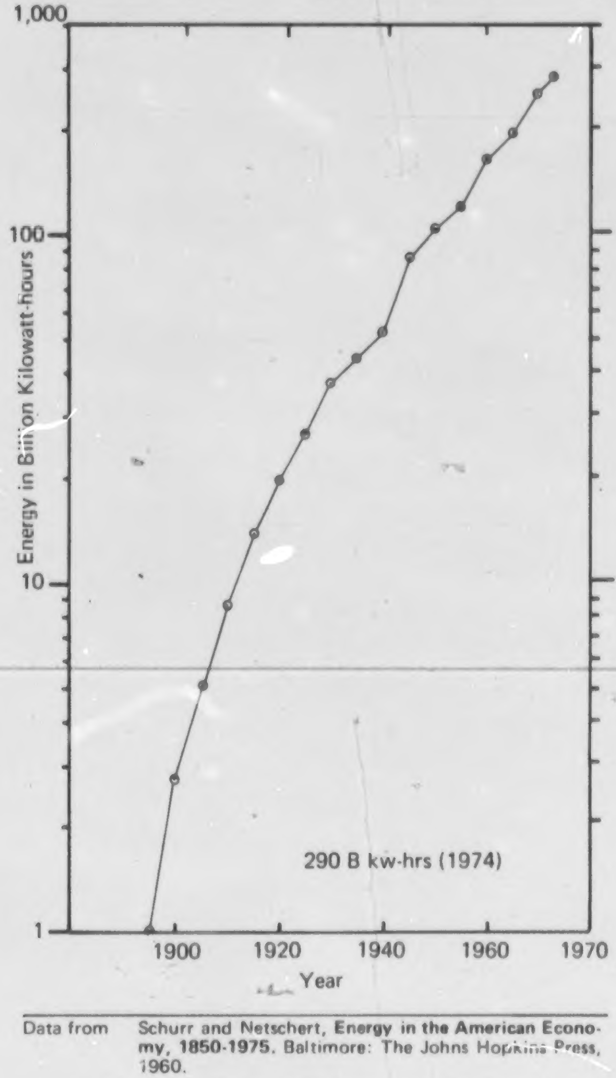
Data from Schurr and Netschert, **Energy in the American Economy, 1850-1975.** Baltimore: The Johns Hopkins Press, 1960.
and Bureau of Mines, U.S. Department of the Interior.

this comparison, we have added the losses incurred in converting primary energy to electricity to the bottom of each column, and display the percentage of the total energy lost through conversion. Because of the increasing use of electric energy, this percentage is also increasing.

Electric energy deserves separate consideration because of its importance as an intermediate form of energy. Figure 4-11 provides a historical record of its consumption in this country since 1900. The consumption of electricity also shows long stretches of exponential increase, broken, as was most energy consumption, by the depression years. Consumption during the 1950s and 1960s showed a 10-year doubling time; during 1960-1970 the doubling time was about 13 years.

The major consumers of electric energy are the household and commercial sectors and the industrial sector. Very little electric energy is used in transportation. We show, in Figure 4-12, the changes that have occurred in the division of the total electric energy between those two groups. In the last 20 years the household and commercial sector has become the dominant consumer, its percentage share increasing from 48 percent in 1950 to 58 percent in 1970. It remained at 58 percent in 1974.

FIGURE 4-10
Electric Energy from Hydroelectric Power



Data from Schurr and Netschert, **Energy in the American Economy, 1850-1975.** Baltimore: The Johns Hopkins Press, 1960.
and Bureau of Mines, U.S. Department of the Interior

The World Picture—Growth and Change

We have, so far, focused our attention on growth and change in the patterns of energy production and consumption in this country. Growth and change are also occurring in the world's energy flow patterns and these are worth a brief report and comparison with the United States data.

We presented the gross energy consumption data in Figures 4-2 and 4-4. The record of the production of energy from the various primary sources is shown in Figure 4-13. The percentage share of the total energy derived from each of the four major primary sources is shown in Figure 4-14.

The gross features of world consumption are similar to those we have just seen in the United States data. The total energy consumption rises steadily, as does the production from the four primary sources. We see from Figures 4-13 and 4-14 that coal is losing ground to oil and natural gas, oil's share having grown from 13 percent in 1925 to 43 percent in 1968, and natural gas's share from 3 percent to 18 percent over the same period. Oil and natural gas production (Figure 4-13) both show almost perfect exponential growth, and their doubling times since 1950 have been about 8 years. Hydroelectric power has contributed only a small percentage of the total, but its total contribution has also risen steadily, doubling every 10 years.

We see in Figure 4-14 only one replacement cycle, the replacement of coal by oil. There existed, of course, an earlier replacement of wood and other organic fuels by coal, but we do not have the data to show this one. The nuclear cycle is only just beginning, it contributed less than 0.1 percent of the world's total energy in 1968.

The omission of data on the "noncommercial" sources of energy, wood in Brazil, cow dung in India, sugar cane residue in Cuba, etc., causes some underestimation of world energy consumption in comparison with the more complete record for the United States. It has been estimated (in 1950) that 51 percent of the energy consumed in Africa was of this unreported, noncommercial type, as was 35 percent of Central America's energy, 45 percent of South America's and 58 percent of Asia's. Since noncommercial fuel is burned very inefficiently, leaving it out does not cause as big an error as one might first suspect.

In a closer comparison between the United States data of Figure 4-5 and the world data of Figure 4-14, we see that the replacement cycles in the world are generally later than similar cycles in the United States. Coal, for instance, dropped below 50 percent of the total in about 1940 in the United States, and by 1960 oil and natural gas between them accounted for 75 percent of the total. The comparable figures for the world show that coal dropped below 50 percent in 1950, and even in 1968 oil and natural gas accounted for only 61 percent of the total. This same lag in the shift to new sources shows up in the production of electricity, which we shall examine next.

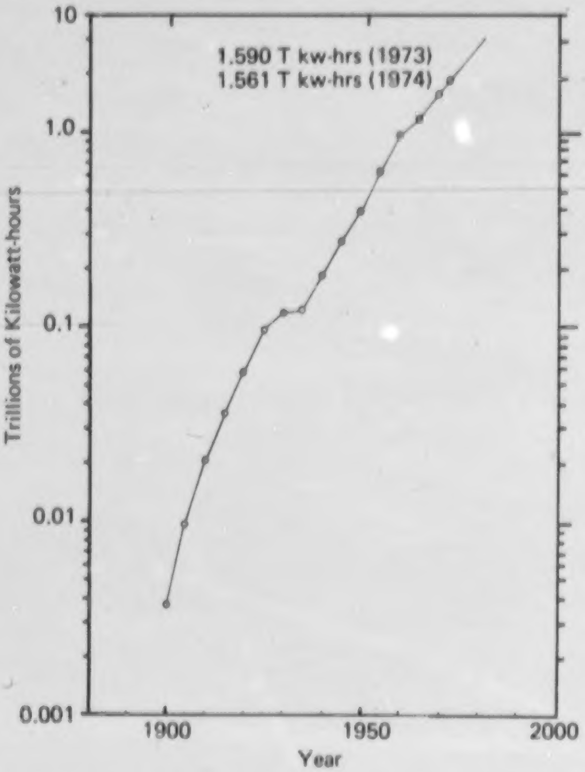
Electric Energy—The World Picture

Following the United States lead, the world is becoming more and more turned on to electricity. Figure 4-15 shows the almost pure exponential growth of world electric energy consumption, with a doubling time of 8 years. Comparison of Figure 4-15 with 4-13 and conversion of kilowatt-hours to Calories shows that in 1968 electric energy (with losses taken into account) accounted for 8 percent of the total world energy consumption, while it accounted for slightly more than 10 percent of the United States total that year.

The absolute values of per capita electric consumption and the growth in this measure are quite different around the world and at home. The data are summarized in Figure 4-16 for the various continents and in Table 4-2 for selected countries. You will note that it is necessary in Figure 4-16 (as it was in Figure 4-13) to use "four-cycle semilog" paper to take care of the great range in data, from the 4 kw-hr per person per year in the Middle East in 1925 to the 7,448 kw-hr per person per year in North America in 1968. Figure 4-16 shows not only the great differences in per capita electric energy consumption between the continents but also the differences in growth. The U.S.S.R., Communist bloc countries, and the Middle East are showing particularly rapid growth, while Africa's electrification proceeds very slowly.

Table 4-2 shows the per capita consumption of electricity in various countries. The highest, twice the United States consumption, is in Norway, where climate and geology provide great hydroelectric capacity, supplying

FIGURE 4-11
U.S. Consumption of Electricity



Data from Schurr and Netschert, **Energy in the American Economy, 1850-1975.** Baltimore: The Johns Hopkins Press, 1960.
and Bureau of Mines, U.S. Department of the Interior.

TABLE 4-1
Energy Consumption by Sectors, 1947-1973 (in Q Calories[a] and Percent[b])

Sector	1947 Q Cal (%)	1955 Q Cal (%)	1960 Q Cal (%)	1965 Q Cal (%)	1970 Q Cal (%)	1973 Q Cal (%)	1974 Q Cal (%)
Household and Commercial	1.81 (25)	2.39 (27)	2.90 (30)	3.47 (30)	4.29 (30)	4.55 (31)	4.42 (29)
Industrial	3.35 (45)	3.82 (44)	4.08 (42)	4.89 (42)	5.91 (41)	6.08 (39)	6.03 (40)
Transportation	2.23 (30)	2.49 (29)	2.74 (28)	3.27 (28)	4.16 (29)	4.78 (30)	4.62 (31)
Subtotal	**7.39**	**8.70**	**9.72**	**11.63**	**14.36**	**15.41**	**15.07**
Conversion Losses[c]	.89 (11)	1.21 (12)	1.46 (13)	1.90 (14)	2.95 (17)	3.39 (18)	3.35 (18)
Grand Total	**8.28**	**9.91**	**11.18**	**13.53**	**17.31**	**18.87**	**18.46**

Data from Bureau of Mines, U.S. Department of the Interior.

[a] Q (quadrillion, 10^{15}) Calories.

[b] The percentages shown for the three consuming sectors are with respect to the subtotal. The percentages shown for the conversion losses are with respect to the grand total.

[c] Hydropower and nuclear power are converted at the prevailing fossil fuel efficiency, which slightly over-estimates the losses.

99 percent of their electricity. Among the other countries, Canada gets 77 percent of its electricity from water power, Great Britain almost none of its respectable amount from that source, and Ethiopia almost all of its paltry consumption from water power.

In the world, as in the United States, we greet the growth in the popularity of electric energy as a mixed blessing. Its growing use is a signal that other people in other lands are beginning to enjoy the benefits of this very flexible form of energy that is so essential in the modern electric world. Generated as it is with inefficient heat engines, however, its growth means that more and more primary energy is being wasted.

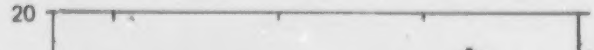
TABLE 4-2
Per Capita Electric Consumption of Selected Countries, 1968

Country	Per Capita Electric Consumption (kw-hrs)[a]
Norway	15,730
Canada	8,450
U.S.	7,175
Great Britain	4,030
U.S.S.R.	3,550
Japan	3,675
Brazil	433
Ethiopia	150
India	94

Source: **The 1968 Statistical Yearbook**, Statistical Office of the United Nations, Department of Economic and Social Affairs, New York, 1969.

[a] kw-hrs = kilowatt-hours

FIGURE 4-12
Consumption of Electric Energy in the Two Major Consuming Sectors



Data from Bureau of Mines, U.S. Department of the Interior.

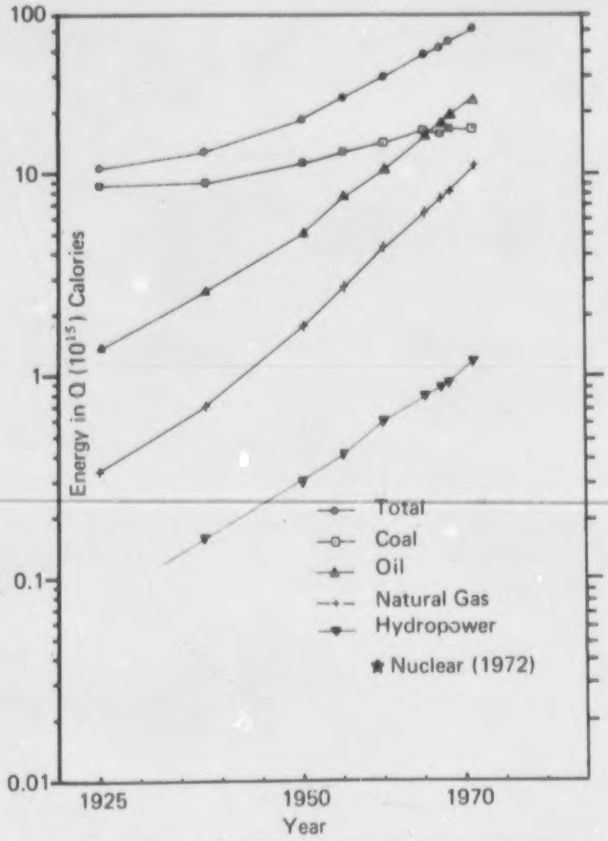
Future Growth—The Hazy Crystal Ball

With the historical record of growth behind us, we can complete our study of energy matters in the "Exponential Century" by looking at the predictions of the growth in demand during the remaining quarter of the century.

If the future takes its cue from the past, we could just plot all the data of production and consumption on semilog paper, lay a ruler along the points, and continue the straight line into the future. Some of the predictions we will look at in this section seem, in fact, to have been produced by that method.

One of the firmest lessons from nature, however, is that exponential growth cannot continue. In terms of

FIGURE 4-13
World Energy Production by Source



Data from Darmstadter, Teitelbaum and Polach, **Energy in the World Economy**. Baltimore: The Johns Hopkins Press, 1971.

and **The 1973 Statistical Yearbook**, Statistical Office of the United Nations, Department of Economic and Social Affairs. (New York: United Nations) 1974.

doubling time, we know that nothing can keep on doubling forever. Exponential growth may take place for a while: a colony of bacteria may double at a constant rate for awhile, the number of uranium nuclei splitting in a "chain reaction" may double at a constant rate for a while. Eventually, however, the reaction from the environment takes over. Food runs out and toxic wastes build up to slow the bacteria growth. Control rods are inserted or the uranium mass blows apart to slow the "chain reaction."

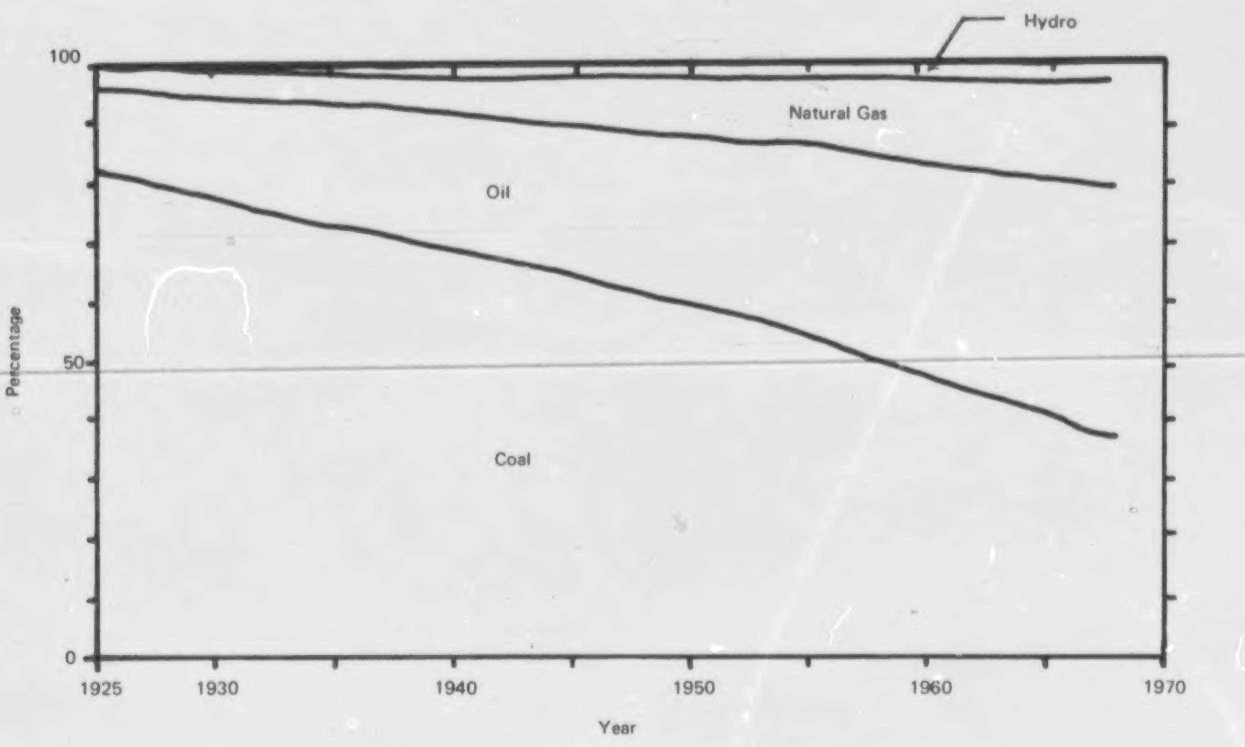
These growth-stunting forces build up in the energy-environment area, also, and we described some of them in Volume I. What do we expect to happen when an exponential growth curve collides with the facts of life? Typically, it turns over and becomes an "S" (or Sigmoid) curve. Figure 4-17, a projection of population growth, provides an example of this. The lessening of the slope, which we see here, means that the doubling time is getting longer and longer, the annual rate of growth (the "interest," so to speak) is getting smaller, and the curve is approaching the stable or no-growth condition of a horizontal straight line. We will look for evidence of such behavior in the projections of demand that follow.

U.S. Energy Consumption, 1970-2000

Prediction is an uncertain art. As we have said, the simplest method is to extrapolate the past into the future. The dangers of this are obvious, as every stock-market speculator or horse bettor knows. More elaborate procedures have been developed; the growth of various components of the economy are individually examined and their contributions summarized, and predictions of overall growth arrived at. The projections we summarize in Figure 4-18 have been made by various experts and have employed many different methods.

The individual projections of total energy consumption in this figure are shown as dots; the x's are the averages. We can make several points from Figure 4-18. The future curve does not yet show the "S" shape; it continues to rise at an annual rate of about 3.5 percent. Another obvious feature is the lack of agreement among experts, which becomes greater as they move further into the future. The predictions for 2000, for instance, vary from a high of 60 Q Calories to a low of 33.8 Q Calories. That this uncertainty is deserved can be verified by looking at the projections for 1970. The four projections shown, all made in the early 1960s, were all low; the extreme one missed the mark by 13 percent. Thirteen percent is not a large error, and yet 13 percent of the 1970 total energy of 17.4 Q Calories is equivalent to 430 M tons of coal, three-quarters of the total tonnage of coal mined that year. Since it is much

FIGURE 4-14
Percentage of World Energy Production from the Four Major Sources



Data from Darmstadter, Teitelbaum, and Polach, **Energy in the World Economy**, Baltimore: The Johns Hopkins Press, 1971.
and **The 1973 Statistical Yearbook**, Statistical Office of the United Nations, Department of Economic and Social Affairs (New York: United Nations, 1974).

more serious to underestimate energy demand than to overestimate it, industries, like the electric utilities, that deal with difficult-to-store energy forms, tend to overestimate demand.

If we stick to the averages as the most realistic projections, continued exponential growth with a doubling time of 20 years is the prediction. Thus, consumption in 2000 is expected to be 1½ times the 1920 total. It is of interest to look at the basic assumptions that underlie these projections. The five most important variables and the assumptions concerning them were:

(1) **Gross national product** (GNP).* Generally, a rate of increase of 4 percent per year was assumed.

(2) **Population.** Generally, the Bureau of Census Series projection of 1.6 percent per year was used.

(3) **Price of fuels.** This assumption refers both to the price of fuel relative to other fuels and to the general price level. Most assume existing relative shares of the market will prevail in the future.

(4) **Availability of fuels.** The usual assumption is that there will be no limitation on gross availability.

(5) **Technology.** Most assume no revolutionary changes, but they do foresee a sizable increase in nuclear generating capacity.

Two other assumptions also seem to have been made; first, that there would be no gross swings in the business cycle, and, second, no major overseas war would occur so defense spending would continue at its present relative level.

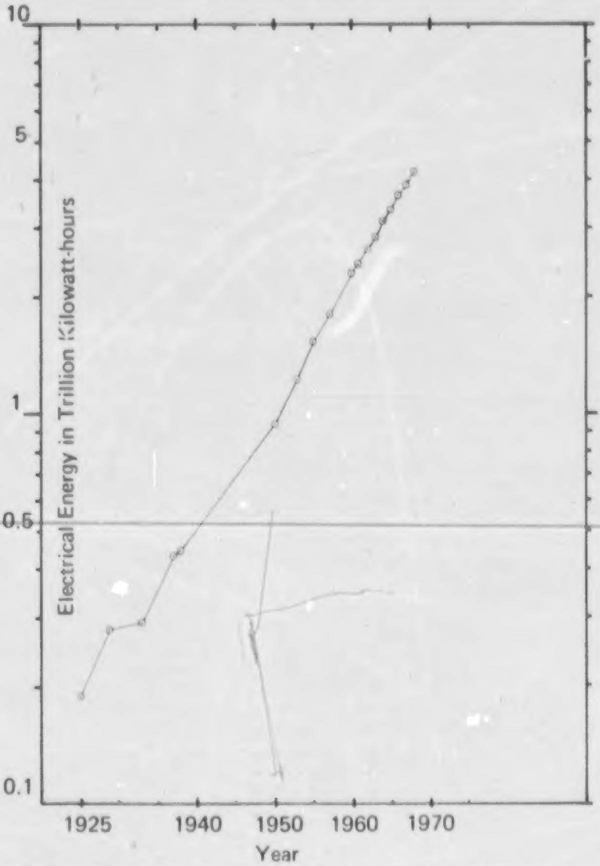
These assumptions seem much more optimistic now than they did when originally made. The 4 percent growth of the GNP, for instance, is much more than the present rate; in fact, the GNP declined in 1974. There is also some evidence that the energy-to-GNP ratio is changing from its historic pattern and that the amount of energy per dollar GNP is now increasing.

The other assumptions can be questioned, also. The 1.6 percent population growth is significantly higher than the actual 1.3 percent growth of the last decade; the assumption of no change in relative prices seems to contradict the presently observable rapid rise of oil prices relative to coal and natural gas. We have just passed through several months of an oil shortage and the threat still hangs over us. The last assumption is surely the most conservative, for by it we give up any hope for help from technology in the next 30 years — no fusion, no fuel cells, no big improvement in electric generating efficiency from magnetohydrodynamic (MHD) generators or other technologies discussed in Chapter 6.

With all these qualifications we can say little about the probable accuracy of Figure 4-18 other than to warn against blind reliance. The net result of most of the changes the past two or three years have brought to the picture — soaring energy prices and general inflation are the most drastic ones — leads to a cautious expectation of less growth than Figure 4-18 shows. The predictions of growth that have come out of the most recent studies, and which we look at in Chapter 7, Volume I, are, in fact, much more conservative than any of these. The change that has taken place in our thinking about our energy future can be seen by comparing Figure 4-18 with Figure 7-3 of Volume I.

As we try to assess these projections and, more importantly, as we look at target areas for energy conservation, it is helpful to look at the three sectors (residential and commercial, industrial, and transportation) separately. Figure 4-19 summarizes a Bureau of Mines projection. There are no great surprises here; all sectors grow, with transportation growing most rapidly. The residential and commercial sector also is expected to grow faster than the industrial sector. These projections, made by the Bureau of Mines in 1968, are already off as far as their absolute numbers are concerned. The actual consumption in 1973 was greater than the projected 1980 total.

FIGURE 4-15
World Production of Electric Energy



Data from Darmstadter, Te[illegible]baum, and Polach, **Energy in the World Economy.** Baltimore: The Johns Hopkins Press, 1971.

and **The 1973 Statistical Yearbook**, Statistical Office of the United Nations, Department of Economic and Social Affairs. (New York: United Nations) 1974.

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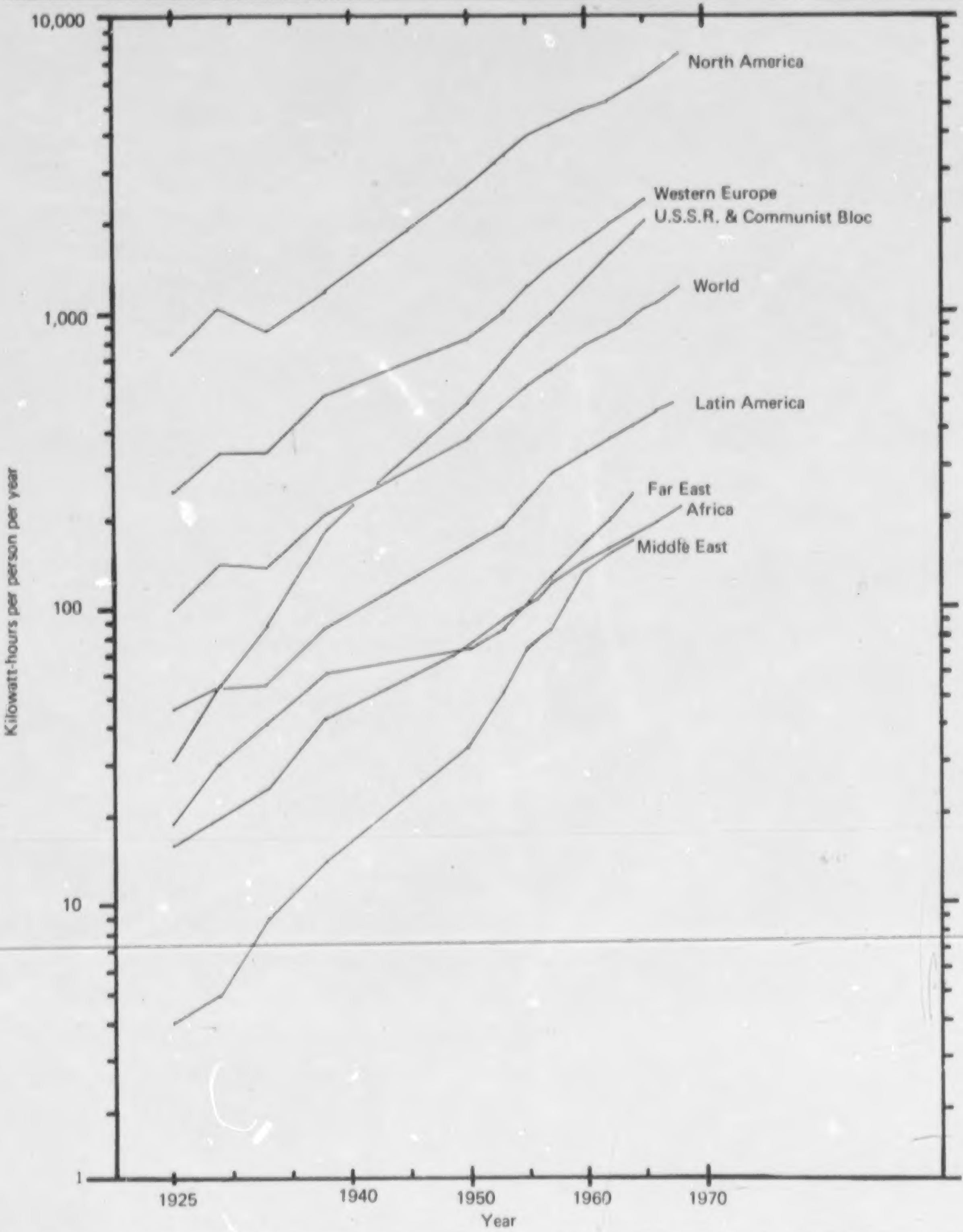
*The GNP is the total value of goods and services produced by a country.

FIGURE 4-16
Per Capita Consumption of Electric Energy in Various Regions



Data from Darmstadter, Teitelbaum and Polach, **Energy in the World Economy**, Baltimore: The Johns Hopkins Press, 1971.
and **The 1973 Statistical Yearbook**, Statistical Office of the United Nations, Department of Economic and Social Affairs, New York, 1974.

2000 and beyond: We will end our crystal ball gazing with Figure 4-20, projections by Ralph Lapp in which the growth of all the forms of energy is individually shown. Total energy curves for different growth rates are shown on it. (He has chosen 2.4 percent per year as the most likely.) Figure 4-20 also shows the peaking of oil and gas production in the early 1980s, and the expected growth of coal and nuclear energy. By this scenario, fuel shares in 2020 would be: nuclear, 48 percent; coal, 24 percent; oil, 11 percent; natural gas, 3 percent, and hydropower 3 percent. A review of Figure 4-5 reveals the great changes Lapp expects in the fuel mix.

Growth in Electric Energy Consumption

In many ways the most troublesome of the growth curves is the one for electric energy. We showed, in Figure 4-11, the impressive historical record of this intermediate energy form, demand doubling every 10 or 15 years. Rising prices, shortage of investment capital, and environmental impact (which we shall discuss later) will continue to attract attention to this sector. What are the projections for its growth?

A summary of expert projections of electric energy consumption is shown in Figure 4-21. The averages fall along a line of 6 percent annual growth, or a 13-year doubling time. Roughly, this means that we will double our consumption of electric energy for 1970-1980, double it again by 1990, and again by the year 2000 — an almost eight-fold increase in 30 years.

FIGURE 4-17a
U.S. Population from 1800

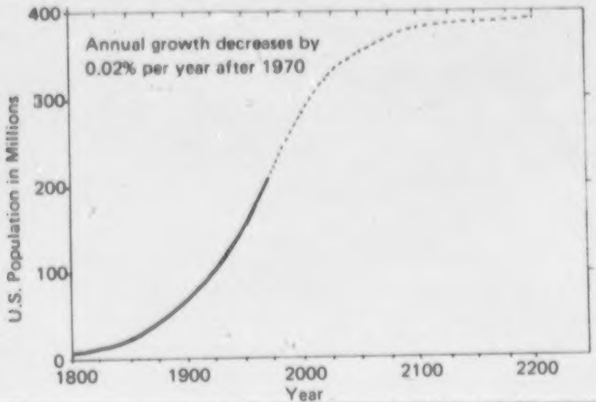
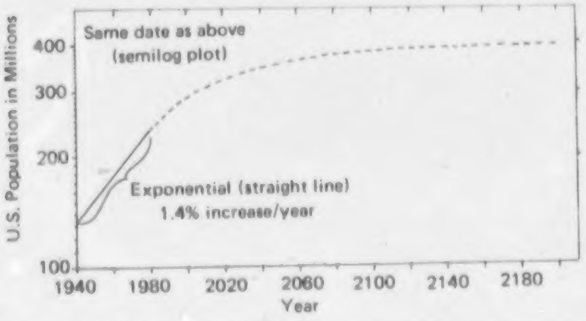


FIGURE 4-17b
U.S. Population from 1940



If we look at our present use of electricity, it is difficult to see how we can use 8 times as much. We can have only so many televisions, toasters, and teakettles. Since electricity is such an important form of energy, it is worth a little space to look in more detail at the causes of its growth.

The Federal Power Commission's projections for growth in electricity demand in the various consuming sectors are shown in Table 4-3. We see that the highest growth rate is expected in the commercial sector, followed closely by the residential, and then the industrial sector. Space heating and air conditioning are the big growth areas in the commercial and residential sectors, with lighting also important in the commercial sector. We have shown, in Figure 3-3, the expected growth in electric space heating and find in these data more support for these projections. There is also room for growth in appliances. In Table 4-4 we show the percentage saturation of various appliances as of 1970. There is clearly room for significant growth in the numbers of air conditioners, food freezers, clothes dryers, dishwashers, and color television sets. The number of appliances will grow as the number of households increases and as the percentage saturation increases. In addition to this, however, the energy consumed per appliance is increasing as they are used more, and as energy-intensive innovations ("frost-free" refrigerators and self-cleaning ovens, for example) are introduced.

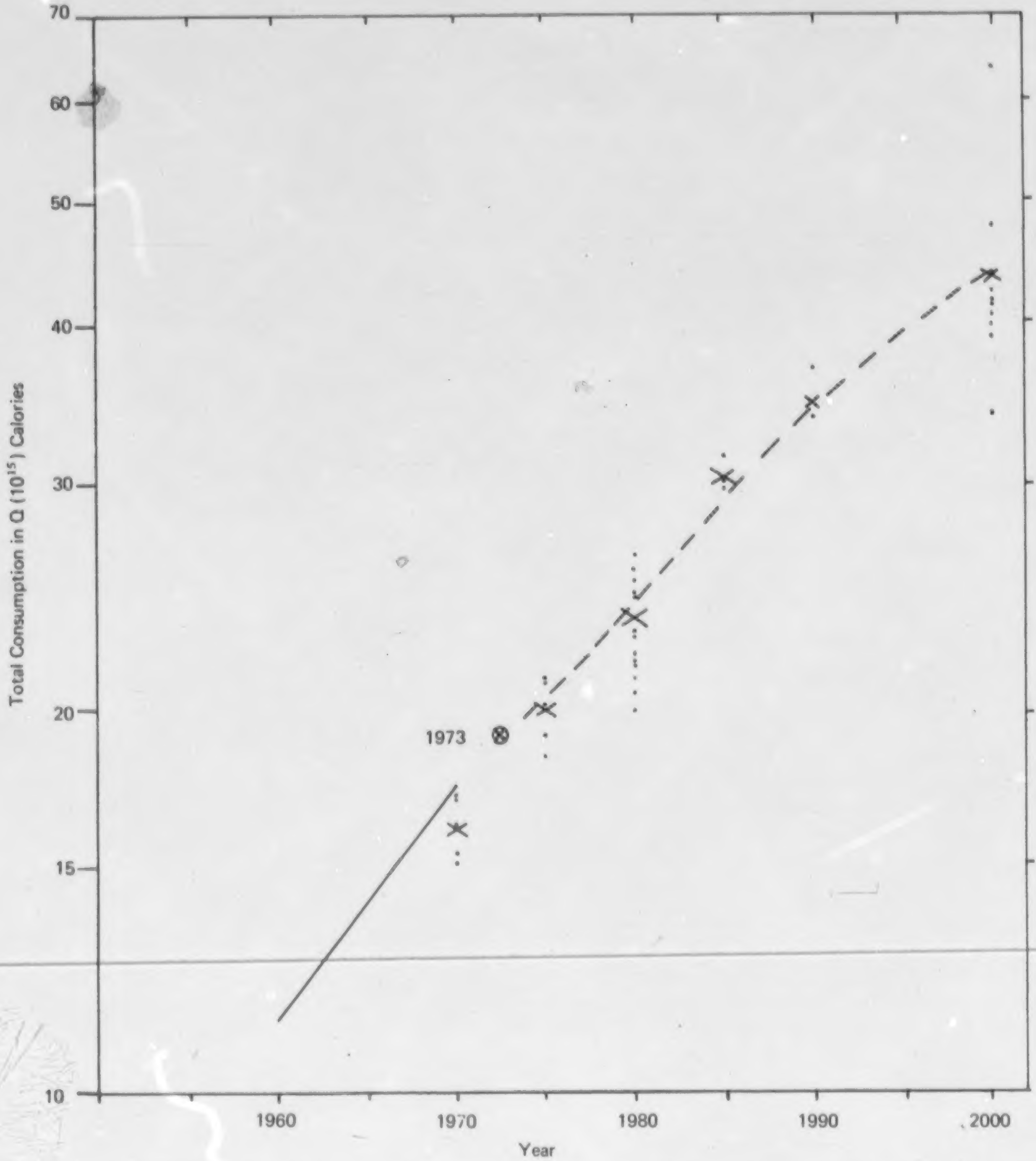
The expensive substitutions: In all sectors, but in the industrial sector in particular, the growth in electric energy consumption is being driven by three different types of substitution: the substitution of electric energy for other direct forms (electric heating for oil, for instance), the substitution of energy-intensive materials for energy economic ones, and the substitution of electric power for manpower.

We have given one example of the first type of substitution. More important ones are occurring in the primary metals industries, where electric furnaces are replacing fuel-fired ones, and in the chemical industry, where new techniques are also electrical.

Much of the growth is spurred by the popularity of energy-intensive materials: aluminum for steel or wood, plastic for paper and glass, synthetic fibers for cotton and wool, etc. We have provided the basis for some of the pertinent energy comparisons in Chapter 3.

It is also clear that electric power has been increasingly substituted for manpower. Between 1947 and 1967, for instance, the electric input to industry doubled, while manpower increased only 14 percent. We find an even more interesting comparison when we look at productivity (defined as the *value added* to goods divided by the manhours input). We show three comparisons of this *value added* (the value of the goods minus the cost of energy, wages, and materials) in Figure 4-22:

FIGURE 4-18
Projections of U.S. Energy Consumption, 1970-2000

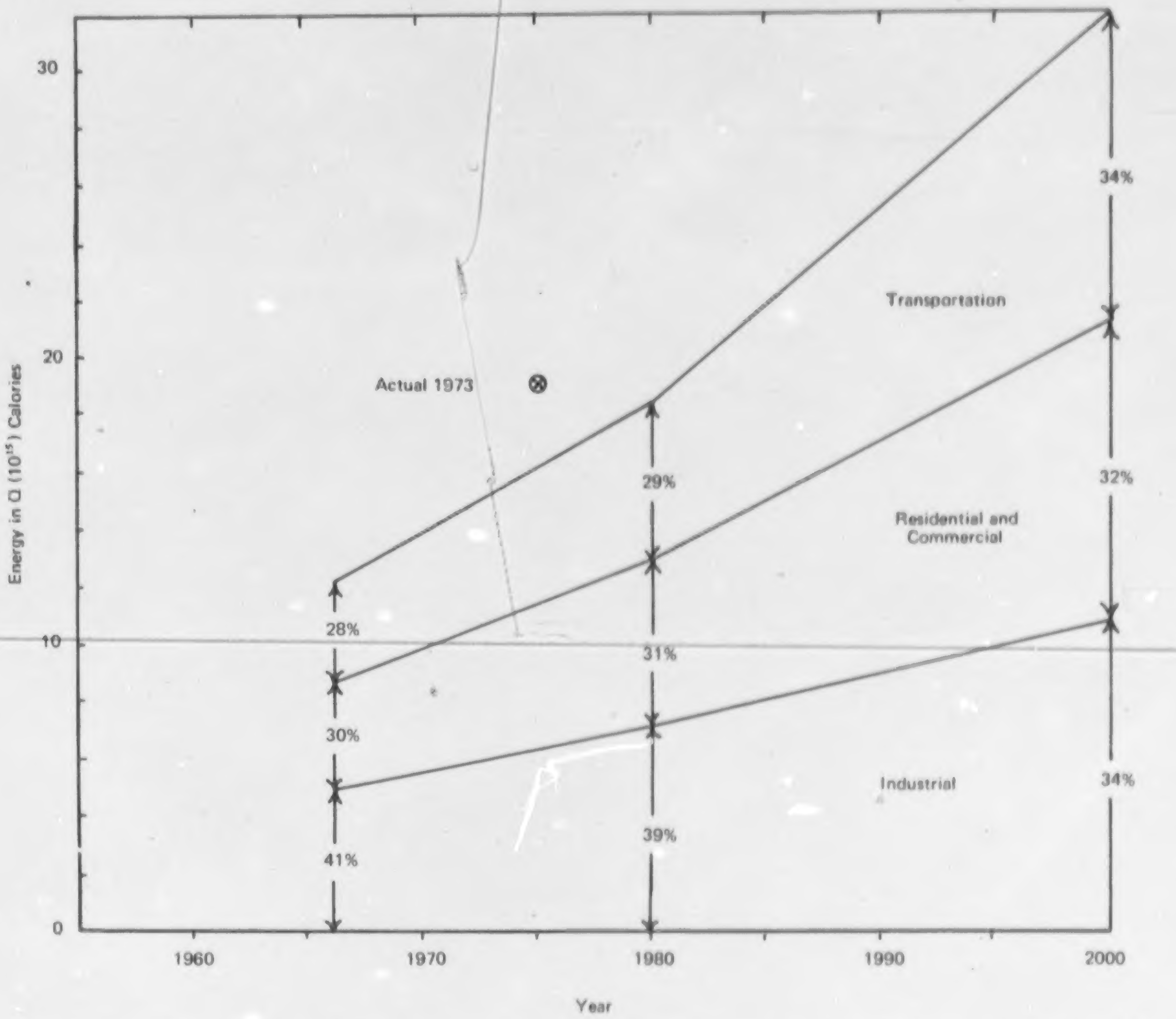


Data from **Survey of Energy Consumption Projections**, Committee on Interior and Insular Affairs, USGPO 94-459, 1972.

"energy productivity," "manpower productivity," and "electric power productivity" (value added per kw-hr). We see that "manpower productivity" has almost doubled over that period, there was a rise of "energy productivity" (during the period of great improvements in energy efficiency) and then a flattening out, and there has been a decrease in "electric power productivity." The implied conclusion is that manpower productivity is increasing because a fewer number of men can multiply their effects with electric devices — and the electric bill rises.

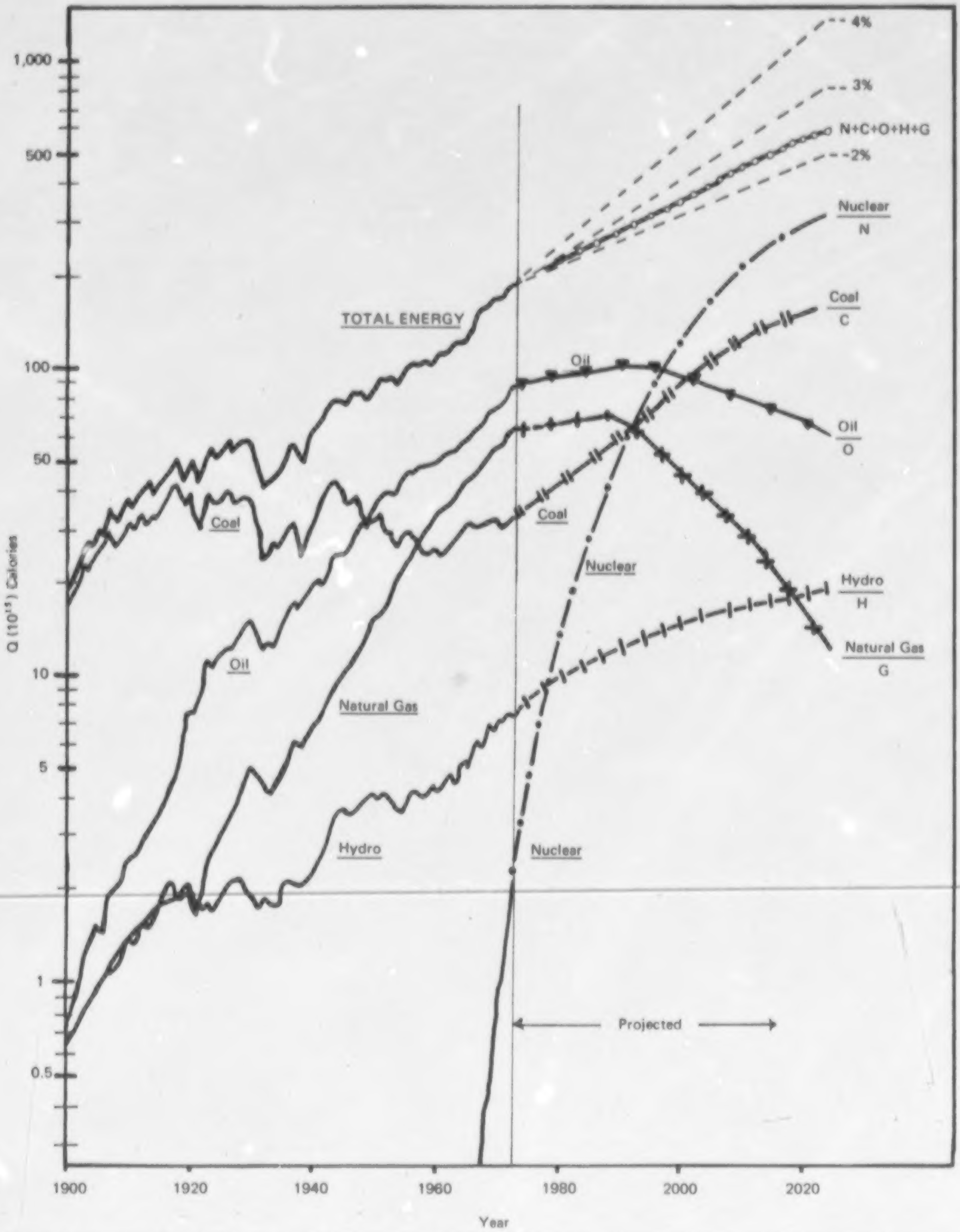
We have discussed electric demand growth in detail because of the inefficient production of this intermediate energy form. To the projection of total electric energy consumed we have added a curve showing the energy that will be lost in the generation of this electricity (Figure 4-21). These losses are an important part of the price we pay for the use of this convenient form of energy. This wasted energy was 17 percent of the United States total energy consumption in 1970, and taking the projections of Figures 4-18 and 4-21 together, we see that in the generation of electricity we will waste 23 percent of our total energy in 1980, 26 percent in 1990, and 33 percent in 2000. The percentage of the total energy wasted grows even though the efficiency of generation improves because of the increased percentage of total energy supplied by electricity. The 14.4 Q Calories of heat that is expected to be wasted in 1990 in the generation of electricity is a little more than the total United States energy consumption of 13.6 Q Calories in 1965.

FIGURE 4-19
Projections of Energy Consumption by Sectors



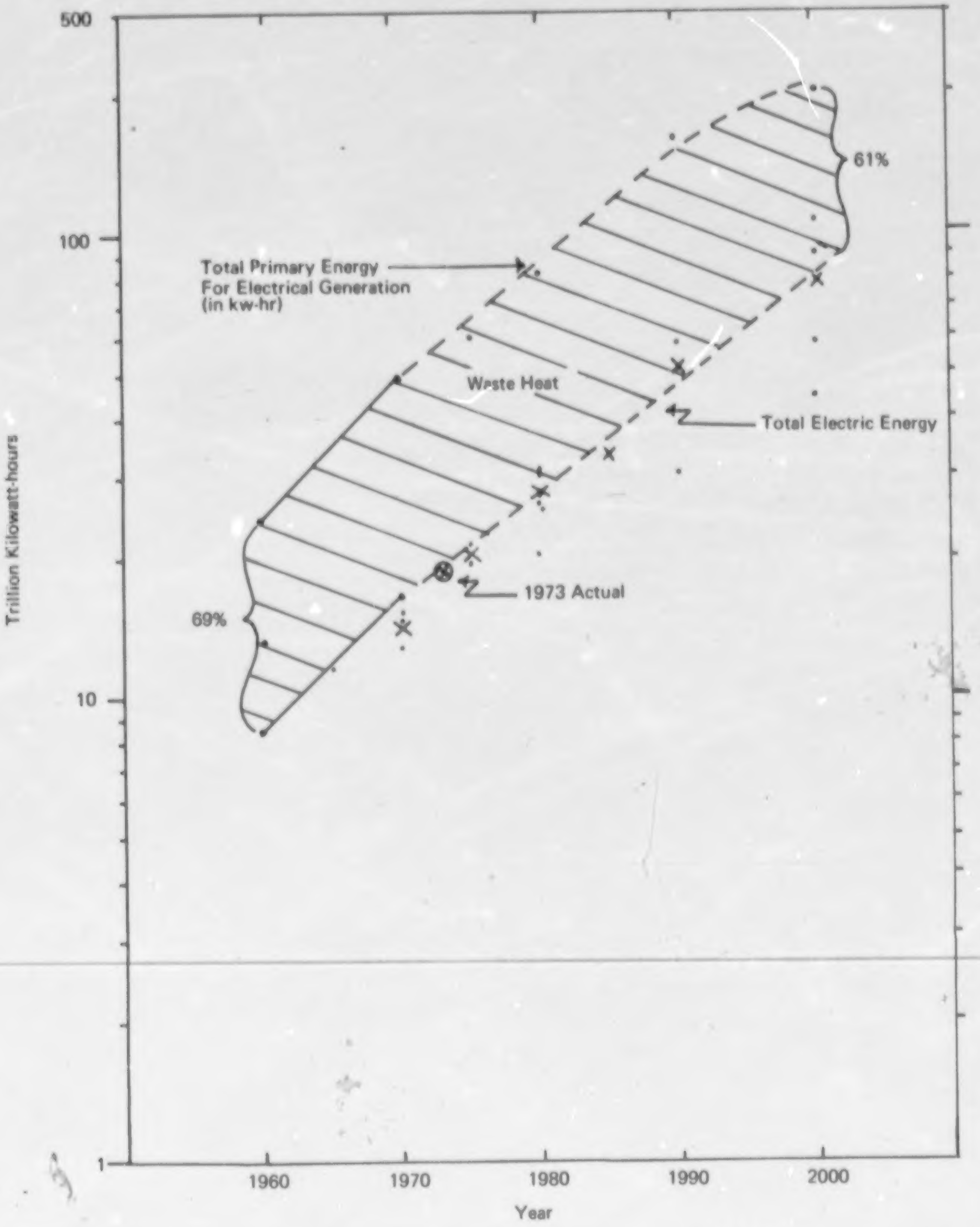
Data from **Survey of Energy Consumption Projections,** Committee on Interior and Insular Affairs, USGPO 94-459, 1972.

FIGURE 4-20
U.S. Energy Scenario, 1974-2024



Source Ralph Lapp, Quadri-Science, Inc., Washington, D.C., private communication, 1974.

FIGURE 4-21
Projection of Primary Energy Use and Electric Production, 1970-2000



Data from **Survey of Energy Consumption Projections**, Committee on Interior and Insular Affairs, USGPO 94-459, 1972.

There are other wasteful uses of energy in our society, and we will focus on strategies for energy conservation in a later chapter. We do, however, want to continually emphasize the price we pay for the convenience of electricity. We should add kilowatt-hours to our energy bill with great care.

A Dissenting Opinion

The rising exponential of Figure 4-21 has other serious implications in addition to the growing waste we have just mentioned. The almost quadrupling of generating capacity by 1990 means four times as many plants, twice as many transmission lines, more air pollution, and radioactive waste. It also makes serious demands on investment capital, building supplies, and manpower.

The electric industry, because it deals with a perishable product, must sell the energy it produces immediately. This fact, combined with the short (about 10 years) doubling time and the long (7 or 8 years) time it takes to put a new plant in line, makes prophesies, such as those of Figure 4-21, to a large extent self-fulfilling. For this reason, these prophesies must be as accurate as possible. There is now reason to suspect that the continued rising demand we have pictured is not completely realistic.

In a study reported in *Science Magazine* (November 1972), three economists, Chapman, Tyrell and Mount, investigated the influence of four factors on the demand for electricity: its price, the growth in population, the average national income, and the price of natural gas. What they were looking for is called the "elasticity" of each of these factors; that is, the percentage increase or decrease in the demand for electric energy that follows a percentage increase in any one of the factors. They found that an increase in the price of electricity *lowered* demand by 1.3 to 1.7 percent for each price *increase* of 1 percent. The other factors showed positive elasticities, demand *increased* with *increases* in the factor. The price of electricity has already begun to rise (after 40 years of decrease) and is expected to rise from 20 to 100 percent in the next three decades.

Using different projections for all these four factors, Chapman *et al*, produced the demand curves of Figure 4-23. We see that all the curves predict similar total electric energy consumption in 1975, but that the projections from their study are three to five times lower than the high estimate of Figure 4-21 for 2000. It is only by assuming a 1.4 percent population increase, and a *decreasing* cost of electricity, that a projection (curve F of Figure 4-22) consistent with Figure 4-21 is obtained.

The most recent data are consistent with the Chapman et al. prediction. In 1974, after decades of growth, electric consumption *declined* 2 percent.

Because of the self-fulfilling nature of electric energy demand projections, it is most important that like studies be continued and that their results be used to shape "official" projections such as those made by the Federal Power Commission.

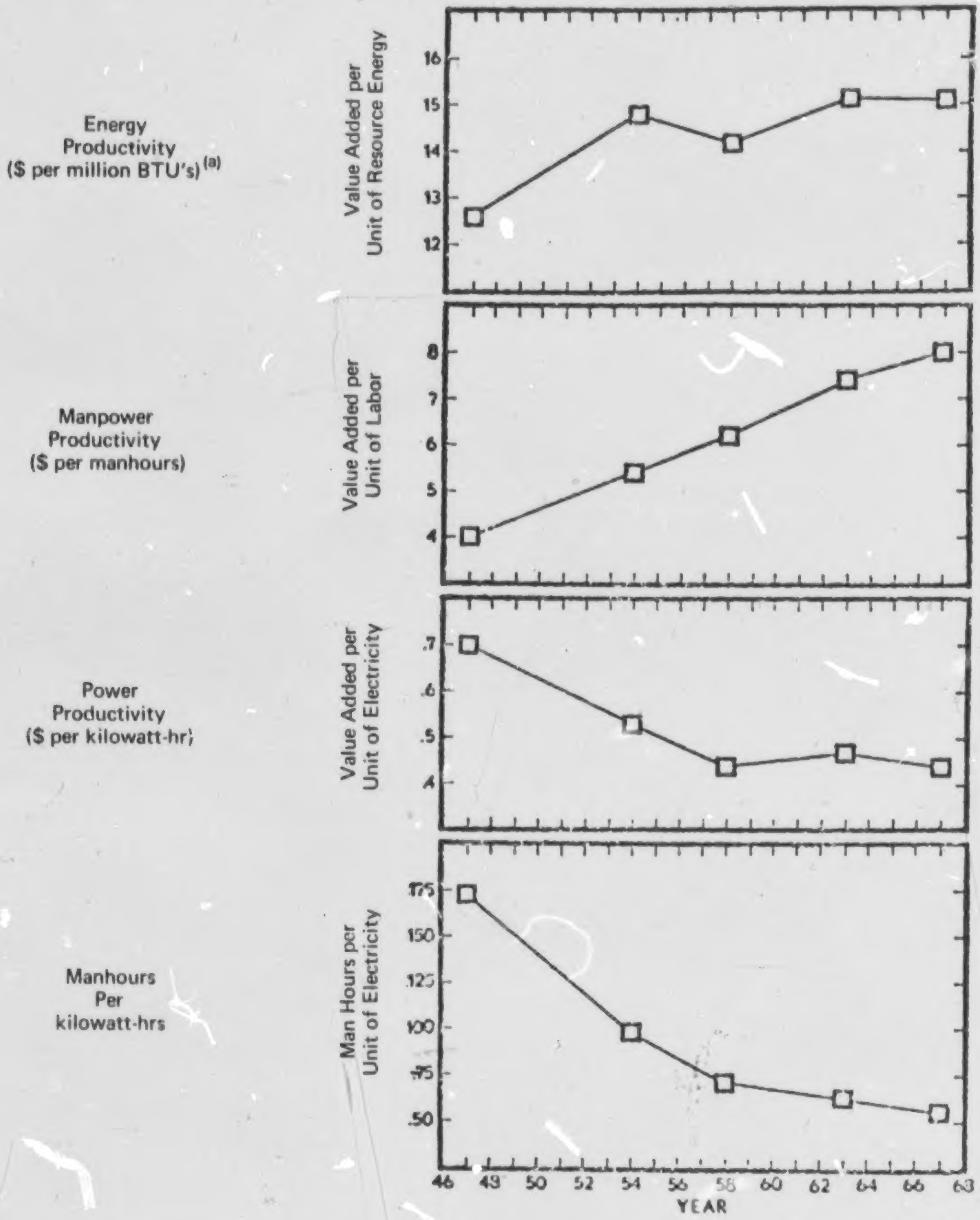
TABLE 4-3
Projected Increases in U.S. Electric Energy Requirements by Classification of Use 1965-1990

Class of Use	Increase in Energy Requirements 1965-1990 (Million megawatt-hrs.)	Increase in Energy Requirements 1965-1990 Percent	Average Annual Rate of Growth (in percent)	Number of Years to Double Consumption
Electric Utilities				
Residential (nonfarm)	1,155	454	7.08	10
Irrigation & Drainage Pumping	23	209	4.62	15
Other Farm[1]	70	259	5.24	14
Commercial	948	498	7.41	10
Industrial	1,950	447	7.04	10
Street & Highway Lighting	31	344	6.14	12
Electrified Transport[2]	3	60	1.90	37
Other Uses	182	569	7.90	9
Losses & Unaccounted for	410	446	7.04	10
Total Utility	4,772	452	7.06	10
Industrial Establishments				
In-Plant Generation[3]	48	47.1	1.55	45
Total	4,820	416.2		

Source: 1970 National Power Survey, Part I, Federal Power Commission, Washington, D.C., 1971.

[1] Includes residential use on farms; other residential uses in rural areas included under "Residential."
[2] Excludes electrification of automobiles.
[3] Excludes industry sales to electric utilities.

FIGURE 4-22
Productivity of U.S. Industry



Source: Commoner, Boksenbaum and Corr, **Energy & Human Welfare, Volume 3,** Chapter 4, MacMillan Information, Riverside, N.J., 1974.

Demand Growth in the Rest of the World

Given the uncertainties we have already discussed, making projections of world-wide energy consumption for the next 25 years is doubly hazardous. The number of political, technological, and economic uncertainties are multiplied and the data and reference values are less reliable.

It is still useful, however, in order to provide some perspective for the supply and resource problems we discuss in the next chapter, to make some projection of world demand. The one shown as Figure 4-24 is based on a population growth of 2 percent per year (slowing a bit toward the end of the century), and a growth in energy consumption of 5 percent during the next decade and 4.5 percent afterward. These growth rates are to be compared with the 3.5 percent projected for the United States (the U.S. data are shown for comparison). They are lower than the growth rate of 5.5 percent the world experienced in the 1960s. We also show, in Figure 4-24, the projected growth in per capita consumption for the United States and the world. We see that although the world total and per capita are growing more rapidly than ours, parity is still many years off.

To complete the world picture we look at two other projections; that of the fuel mix (Figure 4-25) and that of electric energy production (Figure 4-26). The fuel mix picture continues the trends we saw earlier, in Figure 4-14. It reproduces, with a time delay, the United States pattern. Coal declines in importance, oil and gas rise in importance until the 1980s and then begin to decline, and nuclear energy enters the picture, reaching 20 percent of the total (and 40 percent of electric generating capacity) by 2000. This reliance on nuclear energy, given the high capital costs of nuclear plants, may place an intolerable burden on the poorer nations. They will need financial as well as technological help.

The upsurge of electric demand in the world, shown in Figure 4-26, is even more impressive than the projections for the United States we have just looked at. The total and per capita curves are rising at a steeper slope than their United States counterparts; the average world per capita consumption of electric energy will reach, in 1980, the United States level of 1945, and by 2000 will reach the United States level of 1960.

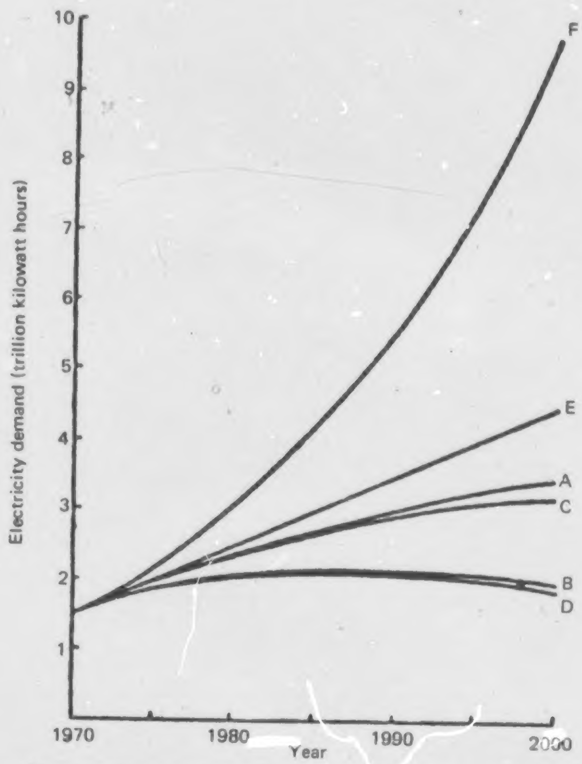
TABLE 4-4
Percentage Saturation of Various Electric Appliances, 1970

Appliance	Saturation (in percent)
Cooking Range(a)	56 (44)
Water Heater(a)	32 (68)
Refrigerator	96
Clothes Dryer(a)	27 (13)
Television	
Black-and-White	141
Color	30
Air-conditioner	41
Clothes Washer	92
Vacuum Cleaner	92
Dishwasher	27
Waste Disposal	26

Source: **The 1970 National Power Survey, Part I,** Federal Power Commission, Washington, D.C., 1971.

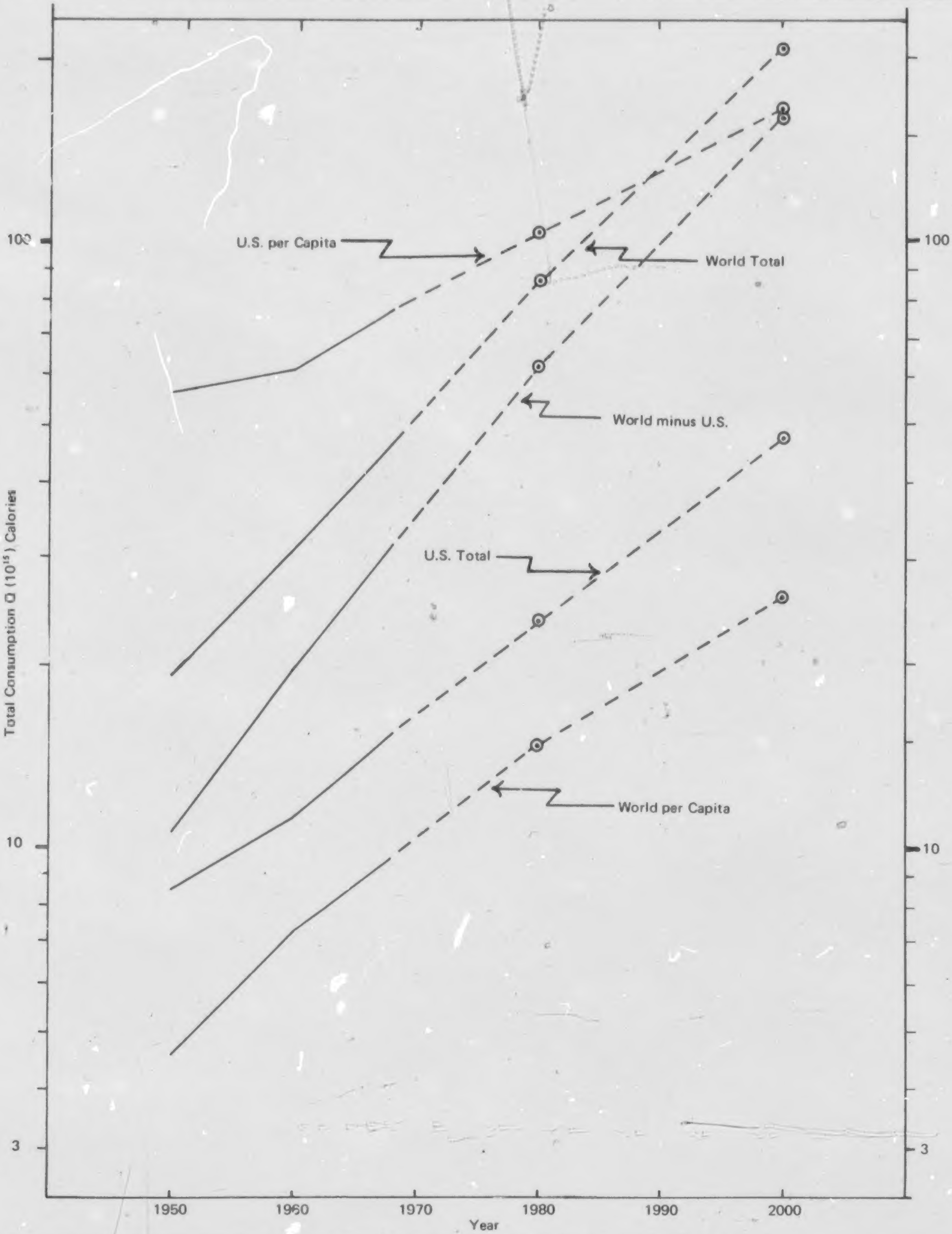
(a) These appliances compete with gas appliances whose percentage saturation is shown in parentheses.

FIGURE 4-23
Electricity Demand Projections



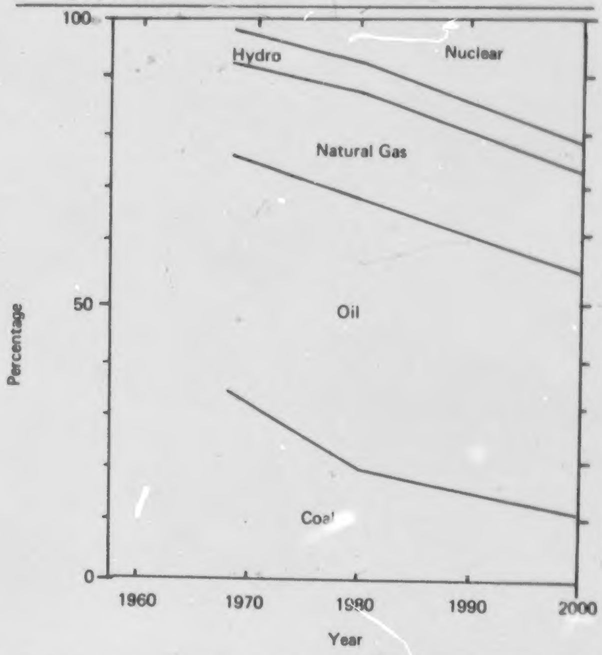
Source: Chapman, Tyrrell, and Mount,"Electricity Demand Growth and the Energy Crisis" Science 178, 703 Nov 1972

FIGURE 4-24
Projections of Worldwide Total and Per Capita Energy Consumption



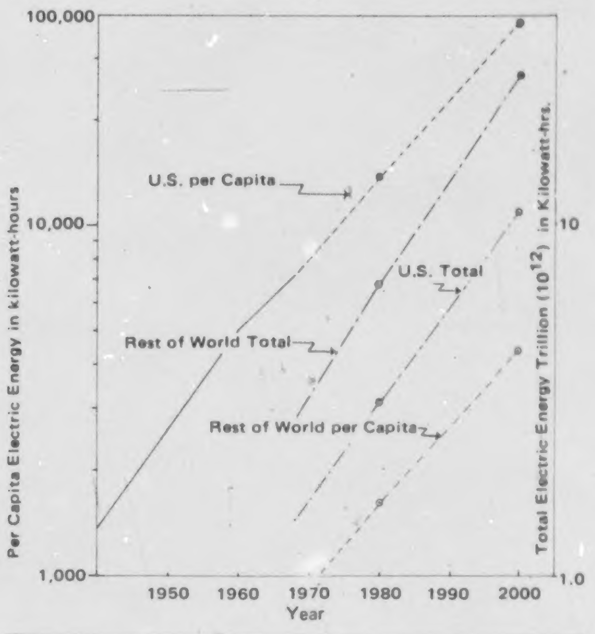
Data from: Darmstadter, Energy, Economic Growth and the Environment, Appendix, Baltimore: The Johns Hopkins Press, 1972.

FIGURE 4-25
Changing World Fuel Mix



Data from: Darmstadter, **Energy, Economic Growth and the Environment**, Appendix. Baltimore: The Johns Hopkins Press, 1972.

FIGURE 4-26
Consumption of Electric Energy U.S. and Rest of World



Data from Darmstadter, **Energy, Economic Growth and the Environment**, Appendix. Baltimore: The Johns Hopkins Press, 1972.

Summary

In this chapter we have looked at the historic records and the future projections of energy production and consumption in this "Exponential Century."

The United States production of energy from the primary sources has grown relatively steadily with a doubling time of about 20 years (if the no-growth period of the Great Depression is neglected). The record of the fuels, however, shows a cyclic pattern; wood replaced by coal, and coal, in turn, by the petroleum products.

The pattern of change in consumption has not been so dramatic in the past 25 years. The industrial sector's percentage share has decreased from 45 percent to 39 percent, while the residential and commercial sectors have increased their combined shares from 25 to 31 percent.

With appropriate cautionary statements, we also looked at projections of energy consumption for the next two and a half decades. Although there was considerable variation in individual projections, the average projections climbed steadily at an annual growth rate of 3.5 percent, and consumption in the year 2000 is thus projected to be 1½ times the 1970 consumption.

The most rapidly growing energy demand is for electricity. Its use has been doubling every 10 or 15 years and this doubling rate is expected to continue throughout the remainder of the century. Demand for electricity is driven by increases in electric space heating, more appliances in more households, important replacements of primary energy by electricity in industry, and a proliferation of electric devices in the commercial sector. Since electricity is presently generated at only 30 percent efficiency from primary energy (this may be 40 percent by 2000), the wasted energy is becoming an important part of the total national energy consumption, growing to 30 percent of the total by 2000.

We looked also at projections of world consumption, which are growing even more rapidly than domestic consumption (at an annual rate of 5.5 percent as against our 3.5 percent). World consumption of electricity is growing rapidly also, signaling the same problems of inefficiency, environmental impact, etc., and the same modernization that the growth of this popular form of energy have in the United States.

Most of the curves we looked at in this chapter showed the straight-line shape in semilog representation that is characteristic of exponential growth. Nowhere did we see the beginning of the no-growth S-curve. Exponential growth of demand, however, cannot continue; it is bound to be slowed by problems of supply or of environmental hostility. We will look at the adequacy of energy supplies in the next chapter.

CHAPTER 5

How Much, At What Price, For How Long?

How Much, At What Price, For How Long?

In Chapter 2 we identified the primary sources of energy in this country, in Chapter 3 we looked at the manner in which we spend this energy, and in Chapter 4 at the historic trends in production and consumption and their extensions into the future. It is now time to take a practical focus and ask for a realistic estimate of our energy future over the short range, between now and 1985. How much oil, gas, and coal can we expect to produce domestically in the next few years, how much of our energy will have to be imported? What are the conditions, especially the financial incentives, that the energy industries will insist on in order to provide this energy. What will this new energy cost us? These are the questions whose answers we will seek in this chapter. With these hard facts in hand, we will then look again at the energy stockpiles of Chapter 2 and try to make a realistic estimate of how long these depletable supplies will last.

The Supply Picture, 1974

Let us, as a starting point, look at the supply picture in 1970 and 1974 by pulling together for our analysis in Table 5-1 some of the data from Chapter 4 and some new data. We see in this table the amount of energy (in quadrillion, Q, Calories) of coal, oil, and natural gas produced domestically and the additional energy (used solely for the generation of electricity) that came from hydroelectric plants and nuclear-powered generators. We also show the additional oil and gas that was imported to meet the demand.

TABLE 5-1
U.S. Energy Supply, Domestic and Imported, 1970, 1973, 1974

Energy Source	Energy Equivalent, Q Calories* 1970	1973	1974
Domestic			
Oil	5.32	5.59	5.32
Natural Gas	5.65	5.47	5.37
Coal	3.30	3.32	3.29
Hydropower[a]	.68	.76	.77
Nuclear[a]	.06	.22	.29
Total Domestic	**15.01**	**15.36**	**15.04**
Imported			
Oil	1.88	3.34	3.26
Natural Gas	.24	.27	.24
Total Imported	**2.12**	**3.61**	**3.50**
Total Consumption	**17.13**	**18.97**	**18.54**
Imports as Percent of Total Consumption	12	19	19
Imported Oil as Percent of Oil	26	37	38
Imported Gas as Percent of Gas	2	5	4

Data from Bureau of Mines, U.S. Department of the Interior.

[a] Kilowatt-hours converted to Calories at average heat rate for steam plants of 2,620 Calories per kw-hr.

*Q quadrillion, 10^{15}) Calories.

The entries indicate the growth in production and consumption we highlighted in Chapter 4; however, they also show the increasingly serious failure of domestic production to keep up with demand. The percentage of our domestic energy consumption that had to be supplied by imports was 12 percent in 1970 and 18 percent in 1973 and 19 percent in 1974. The imports were entirely petroleum products. The 26 percent of oil and oil products imported in 1970 grew to 38 percent in 1973 and 44 percent in 1974. The 2 percent of our natural gas imported in 1970 grew to 5 percent in 1973, but dropped back to 4 percent in 1974.

Where do we obtain these imports? Gas comes in by pipeline from Canada or by tanker carrying liquid natural gas (LNG). The origin of oil is shown by the breakdown in Table 5-2 of crude oil imports for the year 1972. Canada was the largest supplier followed by Venezuela, Nigeria, and then Saudi Arabia. Overall the Arab countries supplied 230 million barrels (M bbls) out of a total of 811 M bbls imported, or 28 percent of the crude oil imported that year. Crude oil accounts for only about 40 percent of the total petroleum imports; that same year we imported 924 M bbls of refined products, chiefly fuel oil of various grades. Most of this came from Western Hemisphere sources, although an appreciable fraction of the crude oil from which these products were refined may itself have come from the Middle East.

TABLE 5-2
Imports of Crude Oil Into U.S., 1972

	M bbls[a]	Percent of total inport
Canada	312.4	39
Columbia	1.7	——
Ecuador	5.3	——
Venezuela	93.3	12
Algeria	31.8	4
Egypt	3.1	——
Lybia	40.1	5
Nigeria	88.9	11
United Arab Emerates	26.9	3
Iran	49.7	6
Iraq	1.3	——
Kuwait	13.2	2
Qatar	1.3	——
Saudi Arabia	63.6	8
Indonesia	59.6	7
Others	19.0	2
Total	**811.1**	**100**

Source: **Energy Facts**, Science Policy Research Division, Congressional Research Service, Library of Congress, Washington, D.C., 1973.

[a] M bbls = Million barrels.

Rough estimates of our overall dependence on Middle Eastern oil in all forms suggest that this region supplied 5 percent of the petroleum products we consumed in 1970, and that this had risen to perhaps as high as 10 percent by the time of the embargo in late 1973. It is well to note and remember the disruption which that embargo, never 100 percent effective, was able to accomplish by cutting off that relatively small oil flow. We summarize some of the effects of the oil embargo in Chapter 1, Volume I.

The gap between domestic petroleum supply and demand is growing. How is it that a country with as large a resource supply as we have tabulated in Chapter 2 has become dependent on imported energy? Can this dependency be removed and self-sufficiency restored? These are the questions we will examine next.

Domestic Production of Oil and Gas

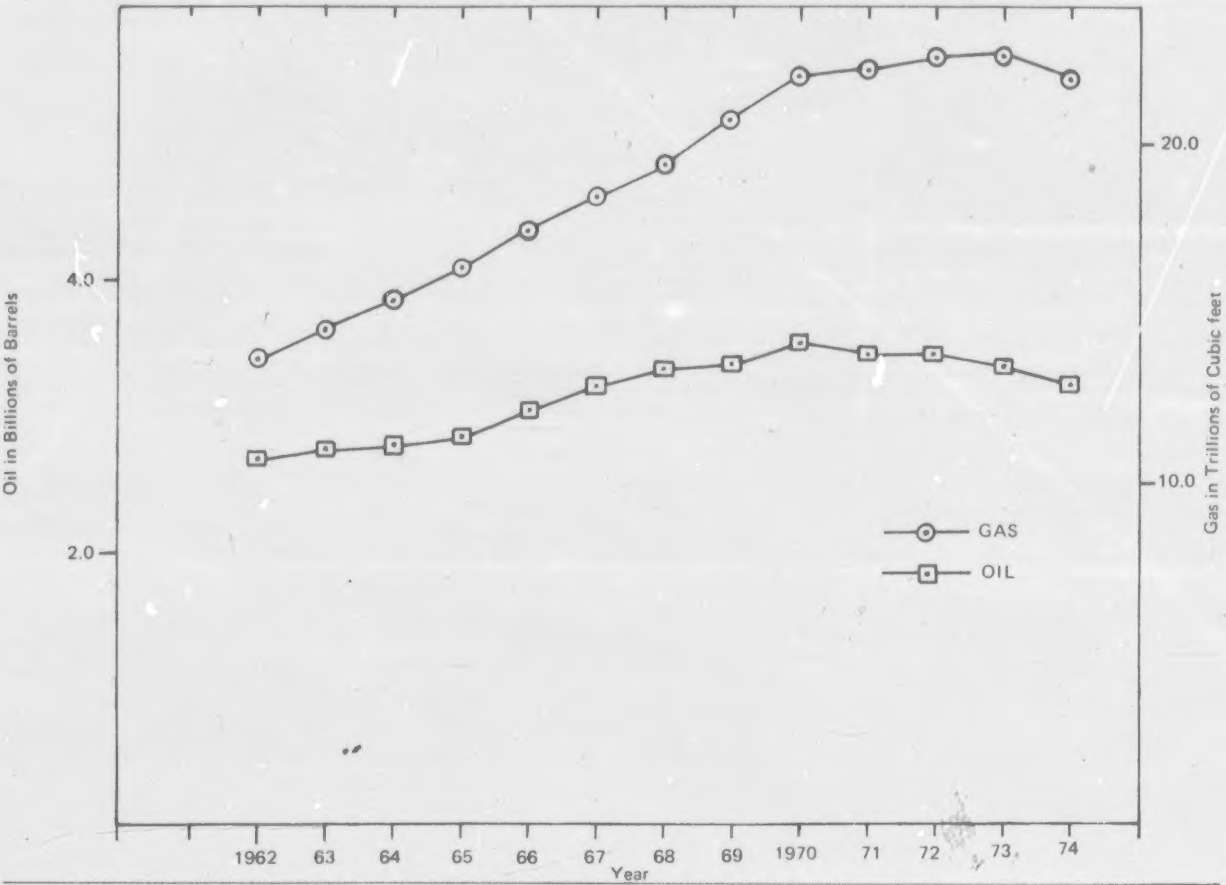
Why did the United States oil industry turn away from domestic production to foreign sources? That it did is not in question; domestic crude oil production peaked in 1970 at 4.12 billion barrels (B bbls) and declined (as shown in Figure 5-1) in 1972, 1973, and 1974. Figure 5-1 also shows a similar peaking in the domestic production of natural gas. This decline is expected to continue at least until the addition, in two or three years, of oil from the Alaskan North Slope field.

One cause for the decline in domestic production is that oil and gas explorations have fallen off in this country. The actual footage of wells drilled has decreased. Figure 5-2 shows these data for oil and for gas. Drilling for oil has been decreasing since 1955; for gas since 1962. Why this has happened cannot be summed up in a brief and simple (and uncontroversial) manner. The underlying causes are, of course, economic, physical, and political with the economic causes dominating. We discussed some of the factors in this decline in Chapter 6 of Volume I.

The main economic cause of the decline in domestic oil production has been the relative cheapness of foreign oil, particularly Middle Eastern oil. The development of overseas production facilities have thus been more attractive to investors.

The reasons for the decline in gas production are similar. Some gas is found with oil, so lowered oil exploration automatically leads to lowered gas availability.

FIGURE 5-1
U.S. Oil and Gas Production



Source: **Energy Facts,** Science Policy Research Division, Congressional Research Service, Library of Congress, Washington, D.C., 1973.

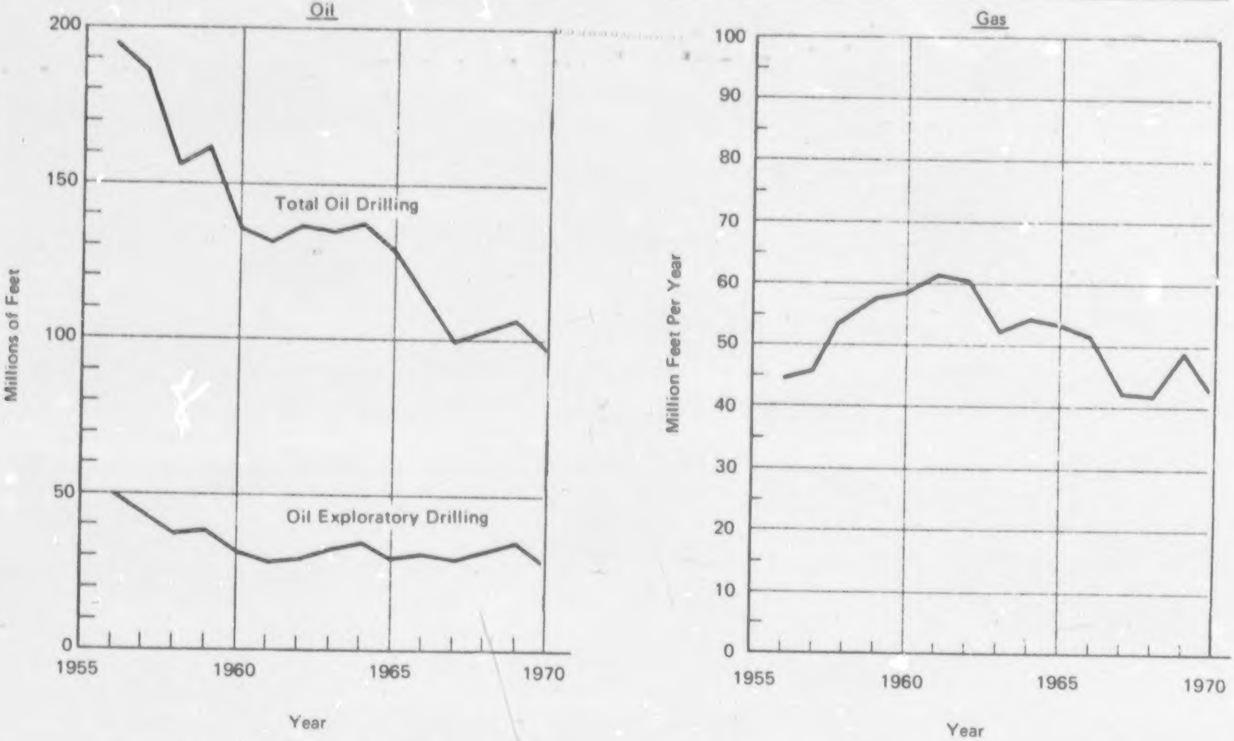
There is a further economic factor in the case of gas. The price of gas is regulated by the Federal Government. This regulation was originally imposed to prevent the industry from obtaining exorbitant profits from gas, which was essentially a low cost by-product of oil exploration. The gas producers now charge that the regulated price of gas is too low and that it does not provide enough incentive for further exploration for, and development of, gas wells. These regulations are now in the process of revision and we shall see if the increased prices, which are sure to result, do stimulate production to meet our needs.

Although these economic factors are probably the most important determinants of domestic oil production, there are other important factors that should be mentioned. The reduction in drilling activity that we have documented has led to a consequent reduction in the number of drilling rigs and of technical manpower. In the past 20 years the number of independent companies engaged in drilling and production has decreased from 40,000 to less than 4,000 and the number of drilling rigs from 5,300 to 1,400. These 1,400 rigs are presently committed for the next year and a half. It will not be physically possible to speed up exploration and drilling until new rigs are built. In addition, bigger and more sophisticated rigs are needed for new drilling areas. The remaining oil to be recovered, as we pointed out in Chapter 2, will be found offshore, in Alaska, or in deeper pools. It will take time to build the new rigs needed for this kind of exploration.

It will also take time and money to develop and implement the secondary and tertiary recovery techniques that can allow the production of more oil from existing reservoirs. These techniques are, for instance, the injection of water or gas to increase the pressure and drive more oil out of the well. As we have also mentioned earlier, detergents are used to reduce the viscosity of the oil to enable it to move more freely; there has even been experimentation with setting thick oil afire in the hope that the heat will drive much of the rest of the oil up the well.

Finally, one should point out that some of the barriers to increased production of oil have come from the so-called "environmental movement." Part of the blame for the shortage of refinery capacity has been laid on this opposition. The fact that the large companies are now building refineries weakens that argument somewhat. It is clear, however, that opposition from environmental interests has slowed the construction of the Trans-Alaskan pipeline and the opening of the Pacific and Atlantic area to offshore prospecting and drilling. The pressure provided by the oil and gas shortages may now be turning the tide to favor the "diggers and drillers" and we may return to the search for fuels as a first

FIGURE 5-2
Domestic Drilling Activity (excludes Alaskan drilling)



Source: **U.S. Energy Outlook,** National Petroleum Council's Committee on U.S. Energy Outlook, Washington, D.C., December 1972.

priority. It is as an alternative to this choice that energy conservation gains some of its support.

As we will see when we look at the supply options put before us by the National Petroleum Council, the decision to increase domestic production is a complex one. It should be made by a public that is well informed and we have tried to develop the most relevant body of information for that purpose in the first volume of this Source Book. With this brief summary of oil and gas production behind us, let us look at the case of coal.

Problems of Coal Production

Domestic coal production has not been under the same demand pressure that has characterized the petroleum industry. With the reconversion of some utilities to coal and the generally increased demand for fuel, it is important, however, to assess that industry's capability and determination to meet demand.

The record of the past few years is not encouraging. Even with the energy crisis upon us, coal production dropped from 595 million (M) tons in 1972 to 590 M tons in 1973 and dropped again in 1974. The goal of "Project Independence," the Federal Government's plan to achieve energy self-sufficiency by 1980, calls for production of 962 M tons of coal per year in 1980. What are the factors that will help or hinder the industry as it tools up to meet that goal?

An expansion of coal production faces some of the same problems that oil and gas producers faced, and many more. The environmental protector's opposition is more direct and more effective. The "Clean Air Act" of 1970 will not allow the burning of much of the available high sulfur coal. Economically viable technology to remove sulfur from exhaust gas is in an early and uncertain stage of development. There is also strong resistance to an expansion in strip mining, particularly in the Western Plains which are the new mining target. The effect of all this opposition combined with the natural pessimism of this industry, which has experienced so many years of declining demand, makes the investment capital necessary for expansion difficult to obtain.

A related problem has already produced effects. Coal is not only dirty, it is dangerous to mine, especially when the mining is done underground. Congress, in 1969, passed a strong "Coal Mine Health and Safety Act." Many mines, especially small mines, have shut down rather than implement the expensive safety requirements.

Coal production is also hampered by a historical lack of research and development emphasis. There was a massive change in the 1950s from manual methods to mining machines, but "long wall mining," for instance, long used in Europe to substantially increase the recovery factor (which is about 50 percent in this country), is only just being experimented with in this country. (In this technique an armored mining machine progresses into a seam and allows the ceiling to collapse behind it. This eliminates the necessity of leaving so much coal behind as pillars.)

Not only does the coal industry face problems of retooling, it also faces a shortage of miners. From a peak of 625,000 miners in the late 1940s, the mining force has dropped to 150,000. There is a specific shortage of young miners. It will take time to open new mines, build new equipment, and attract new workers. The increase in coal production will be slow in coming.

The Fueling of the Next Decade

We have, so far, examined the supply picture as it stood in 1974 (the latest year for which complete data exist), and have described some of the barriers to increased production of domestic coal, oil, and gas. In this section we will present the energy policy options that resulted from an extensive study by the National Petroleum Council, an industry-dominated advisory committee to the Department of the Interior.

In their report, "U.S. Energy Outlook" (December 1972),[1] they investigated the supply-and-demand picture in the light of different assumptions about the various factors that affect domestic energy supplies. They then matched domestic supplies against high, medium, and low demand projections (which cover the range of projections in Figure 4-18.)

Factors influencing domestic production include, for instance; prices, exploratory activities and results, tax laws, environmental opposition to nuclear plants, offshore drilling, refinery construction, etc., and Federal support of research and development in synthetic fuels (the liquid and gaseous fuels made from coal that are described in Chapter 6).

The four supply cases and their assumptions regarding these factors were:

- Case I estimates the possible outcome from a maximum effort to develop domestic fuel sources. Case I assumes oil and gas drilling increases at a rate of 5.5 percent per year, and a high projection of oil and gas discovered per foot drilled. The nuclear power projections are based on the assumption that all new base-load generating plants ordered between now and 1985 will be nuclear. Production of coal for domestic consumption is increased at a rate of 5 percent per year. Synthetic fuels are developed and produced at the maximum rate physically possible, without any restrictions due to environmental problems, economics, etc.
- Case IV, the lowest supply case, assumes that recent trends in United States oil and gas drilling activity, and the success from such efforts, will continue; that the siting and licensing problems with nuclear plants will continue; that incentives to develop new coal mines will not improve; and that environmental constraints will continue to retard development of resources.

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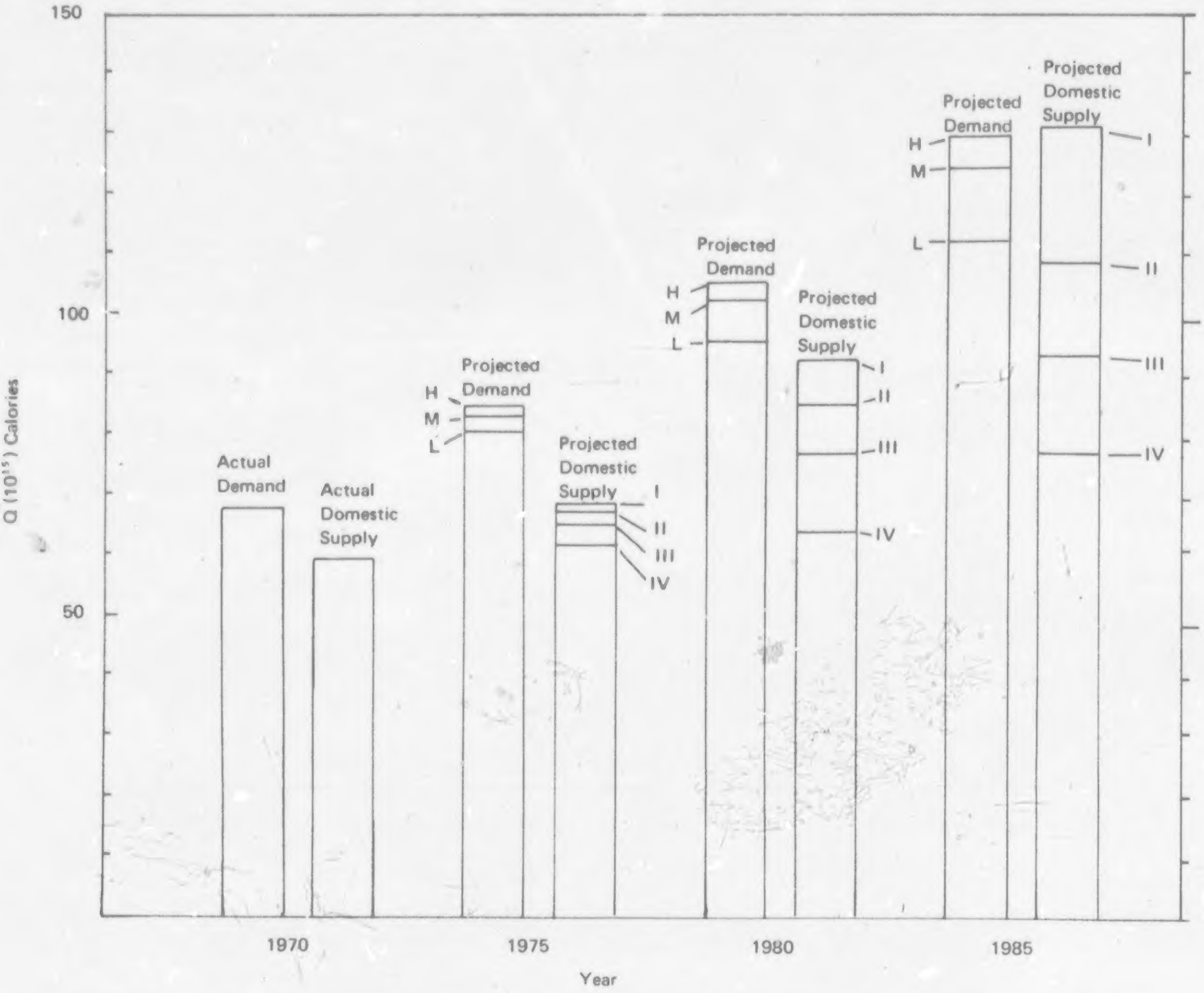
[1] **U.S. Energy Outlook**, A Report of the National Petroleum Council's Committee on U.S. Energy Outlook, December 1972

- Case II assumes a less optimistic future supply picture than Case I. Oil and gas drilling activity grows at a slower rate — 3.5 percent per year — than in Case I but with the same finding rates per foot drilled. For nuclear, Case II assumes problems in manufacture and installation lead times will be solved quickly. Coal production is increased at a rate of about 3.5 percent per year. Synthetic fuels are developed and produced at a moderate build-up rate.
- Case III assumes that there will be improvement over Case IV but not to the level of Case II in the development of indigenous energy supplies. Oil and gas *drilling* grows at the same average annual rate of 3.5 percent per year experienced in Case II, but the trends of oil and gas *finding* per foot drilled are lowered to those of Case IV, which reflect recent actual experience. The development of nuclear power proceeds at about the rate in the AEC's most favorable forecast. There is no significant difference between Cases II and III for coal and synthetics.[1]

In Figure 5-3, the projected domestic supplies of energy from these four cases are matched against projected demand, with the high, medium, and low range indicated. We see in these projections a worsening of the domestic supply situation in 1975. The gap between optimistic Case I and low demand is 14 percent and it falls short of the high demand by 19 percent. The actual gap was 19 percent in 1974. The pessimistic Case IV misses the low demand by 23 percent and the high demand by 27 percent.

FIGURE 5-3
Comparison of National Petroleum Council Supply-and-Demand Projections



Data from **U.S. Energy Outlook**, National Petroleum Council's Committee on U.S. Energy Outlook, Washington, D.C., December 1972.

Note: H, M, & L indicate high, medium and low demand projections
I, II, III, & IV indicate the NPC Supply cases.

The message here is that little can be done in five years to correct our energy imbalance. This is again evidence of the unavoidable delay in bringing about change in the energy picture. It takes five to seven years to open new oil fields or coal mines, build refineries or power plants, etc. Given the green light of Case I, the energy companies promise an improved situation by 1980 and self-sufficiency by 1985. The Case I gap in 1980 between low demand and supply is 4 percent, with high demand it is 12 percent. Case I meets even high demand by 1985.

On the other hand stands the pessimistic Case IV. The gap with low demand grows from 23 percent in 1975 to 33 percent in 1980 and 31 percent in 1985. Case IV will require that we import 40 percent of our fuel in 1985 if we consume at the high demand level.

Unfortunately, the situation is more complicated than this. One cannot make a simple comparison of total supplies with total demand; the fuels are not completely interchangeable — you can't run automobiles on coal or nuclear energy, for example.

What is most interesting is the amount of energy we must import to meet the various demand levels. Since coal and nuclear energy are totally domestic sources, the imports considered were oil and gas. We can gain some idea of the range of possibilities by looking at the extreme cases; the high and low demand and the supply Cases I (maximum supply) and IV (minimum supply).

The specific figures for the percentages of oil and gas imported are shown in Table 5-3. The NPC prediction is that by 1975 we will import about 40 percent of our oil (the 1974 percentage was 44). This will fall to 15 percent of the minimum demand in 1980 and to zero in 1985 for the optimistic supply Case I. The comparable figures for the pessimistic supply Case IV are, assuming minimum demand, 61 percent (1980) and 57 percent (1985). The data of Figure 5-3 and Table 5-3 make the case for the "dig and drill" proponents: the choice is between the optimistic Case I, in which the energy companies are given maximum incentive for exploration and minimum interference from environmentalists, there is a maximum increase (5 percent per year) in coal production, improved finding rates for oil and gas and all new power plants are nuclear, and Case IV, which is the energy company nightmare, where there is no improvement in exploration and finding, there are environmental constraints on both resource development and power plant siting, and so on.

TABLE 5-3
Percentages of Total Energy and Oil and Gas Imported

Supply Case		Percent of Total Energy Imported		Percent of Oil Imported		Percent of Gas Imported	
Demand	Year	Max.	Min.	Max.	Min.	Mas.	Min.
	1975	19.7		42.4		4.7	
I	1980	18.0	9.7	34.7	14.9	12.4	12.4
	1985	14.2	0.9	26.7	0.0	9.5	2.9
	1975	26.0		41.2		5.1	
IV	1980	39.3	33.2	67.4	60.6	17.8	17.8
	1985	40.3	31.1	67.9	56.7	29.2	29.2

Source: **U.S. Energy Outlook**, National Petroleum Council's Committee on U.S. Energy Outlook, Washington, D.C., December 1972.

It should be pointed out that the optimistic supply Case I is indeed optimistic. It predicts, for instance, that oil shale will be producing 750,000 barrels of oil a day in 1985 (4 percent of the total), and that oil from coal will add another 4 percent. The recent pessimism about oil shale and slow progress in coal liquefaction belie these figures. Case I also projects that stimulation of natural gas production by nuclear explosions will add 4 percent to the gas supply, again a questionable assumption in view of the questionable results of preliminary experiments with this technique. The Case I assumption is that 42 percent of the energy to produce electricity will be nuclear in origin by 1985, and this too is a difficult target to reach.

New energy sources that would improve all the projections are not included in the NPC assumptions. There is no expectation of energy supply contributions from solar energy or from organic waste, two potential new sources we will discuss in a later chapter. Such sources are not viewed with much enthusiasm, apparently, by the energy industry.

The Cost of Energy

Whatever route the future takes, whether it goes through Case I and high demand or Case IV and low demand or any of the more likely intermediate assumptions, one thing is certain: the cost of energy will rise. This prophecy will come true whether we are talking about dollars or about cost to the environment. In this chapter we will take a brief look at dollar cost. We have considered some of the environmental cost in Volume I.

There are several aspects of dollar cost. Investment in energy extraction will have to increase, more ships and pipelines will be needed to transport oil and gas, new refineries and utility plants will require money for construction. The NPC estimate of the total capital requirements is summarized in Table 5-4. We see, not surprisingly, that the capital requirements are highest for Case I and lowest for Case IV. What is bought with this capital varies. Case I calls for large investment in exploration and production and in pipelines for natural gas. Case IV has a large budget item for tankers and terminals.

Ships and ports: It is well to pay special attention to the need for tankers and ports to handle the large amount of oil and liquified natural gas that must be imported in the next 10 years. Taking the Case III study for discussion (it is the modestly conservative one), the growth in waterborne petroleum imports will rise from 2.7 M bbls per day in 1970 to 10.7 M bbls per day in 1985. This increase in the total is only one facet of the change that must take place. In the past, most of the tanker deliveries were from Caribbean ports, and small tankers were used in this trade. Since an increasingly large fraction of the oil in the next 15 years will come from the Middle East and Africa, we will have to look more and more to the large tankers that provide the most economical long-distance transport. In Chapter 3, Volume I, we discussed some of the problems supertanker oil shipment will bring.

Not only does economy of transport call for these large tankers, but numbers do also. A 250,000 DWT tankship has a capability of 26 M bbl per day in movement from the Persian Gulf. (This takes into account average travel, loading and unloading time, repair and maintenance, etc.) In 1970 the equivalent of six 70,000 DWT tankers per day had to be unloaded at some United States port to deliver the 2.7 B bbls of petroleum products imported that year. Two of the 250,000 DWT tankers per day could have done the job. Since the amount of imported oil is projected to triple (under Case III) by 1985, the crowding of United States ports will become serious unless large tankers are used. It is clear that deep-water, offshore ports on the East, West, and Gulf Coasts would be highly desirable.

TABLE 5-4

Summary of Cumulative Capital Requirements U.S. Energy Industries 1971-1985 (in billions of 1970 dollars)

	Supply Cases			
	I	II	III	IV
Oil and Gas				
Exploration & Production	171.8	144.8	135.1	88.0
Oil Pipelines	7.5	7.5	7.5	7.5
Gas Transportation	56.6	46.9	39.8	29.5
Refining*	19.0	24.0	30.0	38.0
Tankers, Terminals	2.0	9.0	16.0	23.0
Subtotal	**256.9**	**232.2**	**228.4**	**186.0**
Synthetics				
From Petroleum Liquids	5.0	5.0	5.0	5.0
From Coal (Plants Only)	12.0	4.6	4.6	1.7
From Shale (Mines & Plants)	4.0	2.2	2.2	0.5
Subtotal	**21.0**	**11.8**	**11.8**	**7.2**
Coal†				
Production	14.3	10.4	10.4	9.4
Transportation	6.0	6.0	6.0	6.0
Subtotal	**20.3**	**16.4**	**16.4**	**15.4**
Nuclear				
Production, Processing, Enriching	13.1	11.0	8.5	6.7
Total All Fuels	**311.3**	**271.4**	**265.1**	**215.3**
Electric Generation, Transmission	235.0	235.0	235.0	235.0
Water Requirements	1.1	0.8	0.8	0.7
Total Energy Industries	**547.4**	**507.2**	**500.9**	**451.0**

Source: U.S. Energy Outlook, The National Petroleum Council's Committee on U.S. Energy Outlook, Washington, D.C., December 1972.

*Based on maximum U.S. requirements, some of which may be spent outside the United States.

†Cases I-IV do not include capital requirements for coal production for synthetic fuels. These requirements in billions of 1970 dollars are as follows: Case I–2.0; Cases II/III–0.8; Case IV–0.3.

A second kind of ship has also begun to appear on the ocean, the refrigerated tankship, to haul liquified natural gas. These ships carry natural gas at −260°F (−130°C). By 1980, 40 or so of these ships will be needed (and $2.2 billion to construct them); by 1985, 40 ships more plus an additional almost $2 billion. Total capital investment is doubled with the building of plants, terminals, etc. needed to handle this new material. Large scale delivery of this new form of fuel will begin in 1975, when gas from Algeria (350,000 cubic feet per day) is scheduled to arrive at a Texas port for use by the El Paso Gas and Electric Co.

The offshore ports, the increased transoceanic shipment of oil, and the liquified natural gas all raise the prospect of the new environmental problems we discuss in Chapter 3, Volume I.

Exporting money: There is another serious financial implication of this supply picture: the money we will have to spend to buy this imported oil and gas.

In 1970 the United States imported $3.4 billion worth of oil and $0.2 billion of gas and exported oil products and coal worth $1.5 billion for a net energy-trade deficit of $2.1 billion.

In 1975 the energy-trade deficit for the four cases, it is estimated, will grow to between $9.4 and $13.1 billion. This is two or three times the total 1974 balance of trade deficit of $4.7 billion.

Except for Case I, these deficits are expected to grow each year. Trade deficit estimates for 1985 are shown in Table 5-5. It must be remembered that these are yearly figures. The international as well as national problems that may grow from such huge transfers of capital are discussed in some detail in Volume I of the Source Book.

Prices: The large amounts of money we have been discussing will, of course, have obvious repercussions in the price of energy. Figure 5-4 shows the recent

TABLE 5-5

Balance of Trade Deficit in Energy Fuels, 1985 (in billions of dollars)

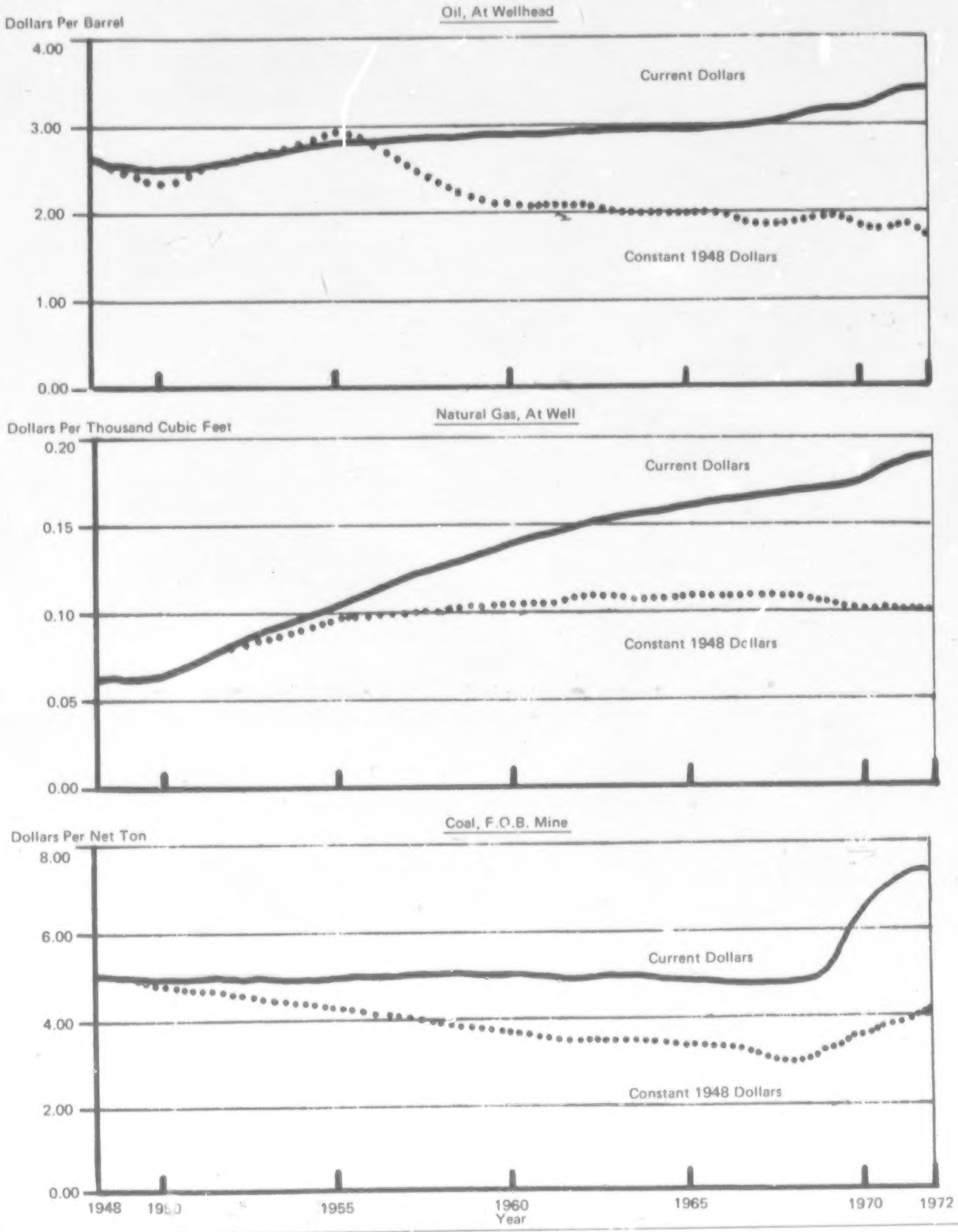
	Case I	Case II	Case III	Case IV
Oil Imports (delivered)*	5.4	13.1	20.4	29.1
Natural Gas and LNG Imports	4.9	5.0	5.3	5.4
Total Energy Fuels Imports	**10.3**	**18.1**	**25.7**	**34.5**
Oil Exports	(0.4)	(0.4)	(0.4)	(0.4)
Steam Coal Exports	(0.3)	(0.3)	(0.3)	(0.3)
Metallurgical Coal Exports	(2.1)	(2.1)	(2.1)	(2.1)
Total Energy Fuels Exports	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**
Total Energy Fuel Deficit	**7.5**	**15.3**	**22.9**	**31.7**

Source: **U.S. Energy Outlook**, National Petroleum Council's Committee on U.S. Energy Outlook, Washington, D.C., December 1972.

*Including synthetic gas feedstocks.

FIGURE 5-4

Average Values of Oil, Gas, and Coal, in Current and Constant Dollars*



Source: Resources for the Future, 1973 Annual Report, Washington, D.C., pg. 35.

* Current dollars are actual prices, constant 1948 dollars are corrected for inflation.

historical record of the price of the fossil fuels and electricity. Recent increases, even in terms of constant dollars, are striking. The projections for the future, however, could be characterized as "you ain't seen nothing yet." The NPC projections for price rises (in terms of constant 1970 dollars) are:

Oil at the wellhead: up 60 to 125 percent
Gas at the wellhead: up 80 to 250 percent
Coal at the mine: up about 30 percent
Uranium ore: up about 30 percent

To these projections we can add a 1970 one from the Federal Power Commission: the price of electricity will increase by 19 percent by 1990 in terms of constant 1968 dollars. The price increases in the two years since the FPC projections make their forecast seem overly conservative.

To give a consumer's picture of what this means, we show in Figure 5-5 the historical record of typical consumer prices of gasoline, fuel oil, and electricity. The mathematically minded reader can use these data and the percentages noted above to estimate his 1985 energy bill — a most depressing exercise. High prices, however, may be the most effective incentive for energy conservation.

The Fossil Fuels—How Long Will They Last?

As a final note in this chapter on supply and demand, we will look again at the stockpiles and estimate their lifetimes under various conditions of growth. It is not our intention in this section to make the typical "doomsayer" prediction: "In X years we will run out of oil." What we wish to demonstrate is that the stockpiles are limited and that *at present rates of consumption* they conceivably could be exhausted within the lifetime of students in school today.

Oil

We will start with the fossil fuel on which most of our attention is now focused. From Table 2-3 we see that at the last accounting (1972) our oil reserves were 52 B bbls and it was estimated that there were 502 B bbls of oil in the "ultimately recoverable" category. Oil consumption in 1973 (including imported oil) was 6.3 B bbls. At that *constant* rate of consumption the reserves, if we drew all our oil from this domestic supply, would only last eight years and the ultimately recoverable stockpile would be gone in 80 years. This assumes a constant rate of consumption; our rate of consumption is actually increasing. We saw from Figure 4-8 that the doubling time was about 16 years over the past decade — an annual growth rate of 4.4 percent. If we assume that this growth rate continues, how long will the oil last?

This problem is analyzed in an old riddle. A farmer has a pond with a lily pad on it. The lily pad doubles in size every day and the farmer knows that in 30 days it will completely cover the pond. He does not want this to happen but is so busy that he decides to wait until it covers half the pond before he cuts it out. When will the lily pad cover half the pond? Since it doubles every day, it will cover half the pond on the 29th day. The moral for the farmer is, of course, that he must take his corrective action within that one day or his pond is lost. There is a lesson in this for us as well.

We can use the lily pad analogy. A day for us is a doubling time; we'll use the 16 years that was characteristic of oil in the past decade. From 1958 to 1973, we consumed 73.3 B bbls. This is about 15/100 of our ultimately recoverable resources of 502 B bbls (see Table 2-3). In one doubling period — 16 years from now — we will have used 30/100 of our supply and in the next 16 years we use 60/100 more. In 40 years, therefore, 90 percent of the ultimately recoverable resource will be gone (90 percent of the farmer's pond is covered). It is clear that the total will be used up well before the end of the third doubling time. From this crude estimate we can say that, at the present rate of demand growth, 4.4 percent per year or a 16 year doubling, the ultimately recoverable resources of oil (Table 2-3) will last only about 35 years. Given this example, and remembering the relationship between annual growth rate and doubling time (see Chapter 4), T_{double} = 70 years divided by r (percent per year), the reader can calculate resource lifetimes for other assumed growth rates.

Before we apply this technique to natural gas and coal, we should remind the worried reader that the previous calculation assumed that we get all our oil from domestic sources. If we import half of it, the supply will last twice as long.

We cannot, of course, import oil forever; world supplies are also finite. The total world oil stockpile, Figure 2-14, is equivalent to about 3,000 Q Calories of energy. World oil consumption has, in the past few years, doubled about every nine years. In the most recent doubling time (1959-1968), the world used about 110 Q Calories of oil, or about 4/100 of the total ultimately recoverable resources. In the first nine-year doubling time (1968-1977), 8/100 of the total will be used, by 1986, 8 + 16 or 24/100, and by 1994, 24 + 32 or 56/100 of the total, a little more than half. All will be gone before the year 2003. We can thus estimate the world oil supply lifetime to be less than 35 years (1968-2003). This short lifetime for world supply is caused by rapid growth, nine years doubling instead of 16, used in world calculation. Since the numerical estimates are rather crude, the only meaningful conclusion we can draw is that the world will not be able to make up our production-consumption deficit for very many years.

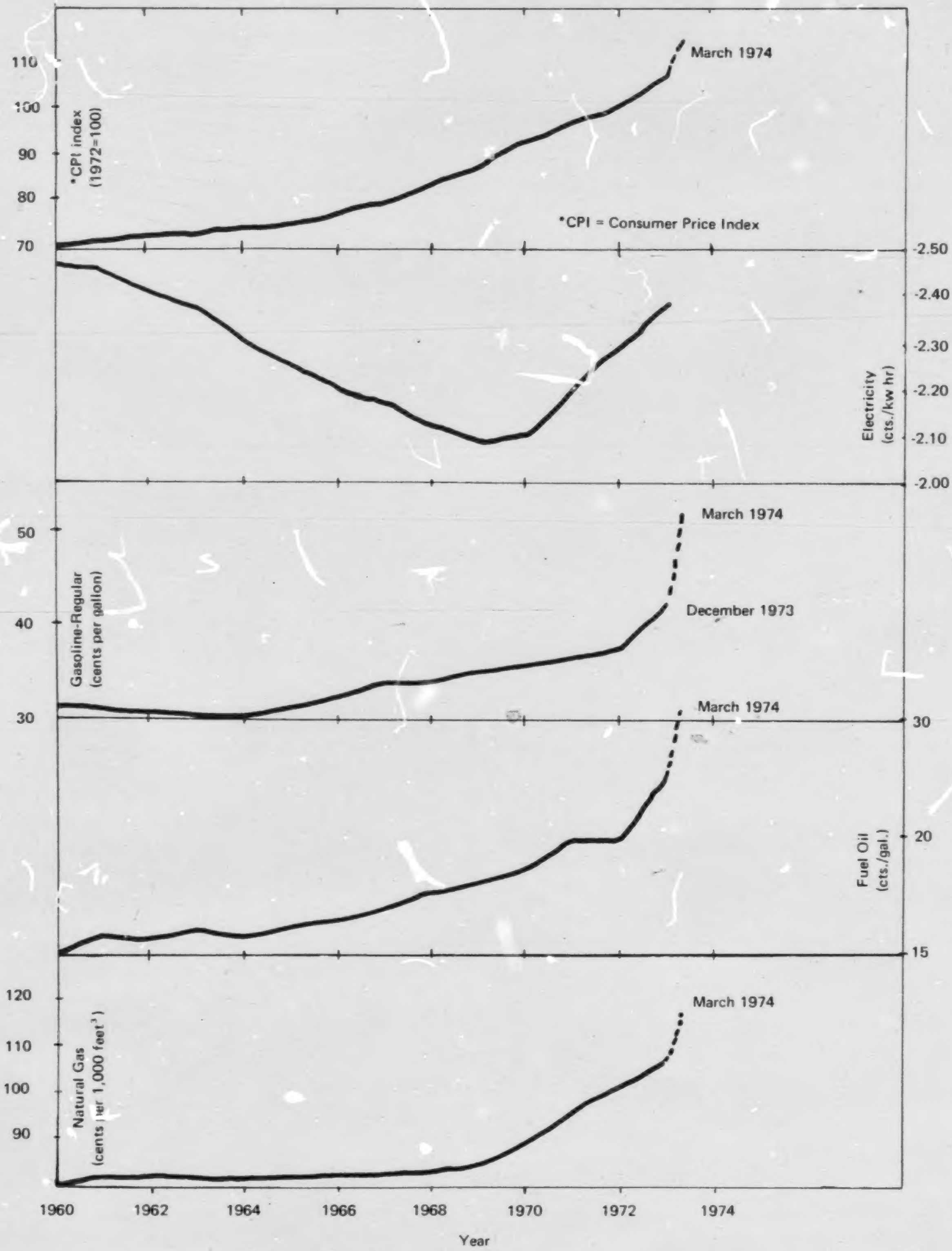
Natural Gas

We can apply the same technique to demonstrate the short future of natural gas as a fuel. The total reserves, from Table 2-4, are 290 trillion (10^{12}) cubic feet (TCF) and 2,560 TCF ultimately recoverable resource. Consumption in 1973 was 22.9 TCF. Thus, at this *constant* rate of consumption the reserves will last about 13 years and the ultimately recoverable resources 112 years.

To make the "lily pad" calculation we need the doubling time, about eight years from Figure 4-9. In the past

FIGURE 5-5

Average Residential Prices of Fuels and Electricity (in current dollars including taxes)



Source: Bureau of Mines, U.S. Department of the Interior.

doubling period (1963-1970) we consumed 159.7 TCF, about 7/100 of our ultimately recoverable resource. Thus, in the next eight years (1970-1978) we will use 14/100, and 28/100 more in the eight years after that, for a total of 42/100 consumed by 1986. This is almost half the total, so before the end of the next doubling time, by 1994, the gas will be about gone; at this rate of consumption it is projected to last only about 30 years.

We can make a similar rough estimate of the lifetime of world natural gas resources. The ultimately recoverable resources of Figure 2-9 are about 3,500 Q Calories. World consumption doubles every nine years and during the past nine years 57.3 Q Calories were consumed, 16/1000 of the total. If we double this, 32/1000 are gone by 1977, 32 + 64 or 96/1000 by 1986, 96 + 128 or 224/1,000 by 1994. Continuing, we find that 480/1000 or just about half is gone by 2003 and, thus, it all will be essentially gone by 2012. The lifetime of the world ultimately recoverable resource of natural gas is, thus, about 45 years.

Coal

The reserves of coal, which we showed in Table 2-2, amount to 390 B tons. Consumption in 1973 was 563 M tons. Thus, at this constant rate our coal reserves will last 693 years. There are no additional ultimately recoverable resources of coal.

Coal consumption has fluctuated greatly, so the application of doubling time to coal carries little meaning. We can use the National Petroleum Council's Case I (optimistic estimate) supply to gain some perspective. They assume (see Chapter 4) that coal production increased at 5 percent per year. This gives a 14-year doubling time (70 years/5). During the past 14 years (1960-1973), we produced 7,130 M tons, or about 2/100 of the reserves. Thus, 4/100 will be used up between 1973 and 1987 and 12/100 by 2001. Following through the calculation we find that 60/100 are gone by 2029; thus, the period 2029-2043 is the 29th day. All the coal (at this rate of production) will be gone before 2043, 70 years from now.

We must remind you again that this estimate is based on the 390 B tons of coal in the reserves; new mining techniques will probably open up more of the 3,200 B tons of total resources. It also uses the very high growth rate of 5 percent per year that is unlikely to continue into the next century. The calculation shows, however, that even coal is not inexhaustible.

During the past decade the world has consumed coal at a fluctuating rate, also, and so we cannot apply our "lily pad" calculation. Consumption was nearly constant, in fact, between 1963 and 1968, averaging about 2,460 M tons per year, or 15 Q Calories per year. At that constant rate, the 54,000 Q Calories of Figure 2-14 will last 3,600 years.

TABLE 5-6
Resource Lifetimes, U.S.
("Ultimately Recoverable Resources")

Resource	Lifetime (in years) Constant 1973 Consumption	With Increased Consumption	Doubling Time for Column 2
Oil	80	35	16
Natural gas	112	30	8
Coal	693	70	15
Uranium*		27	3

*Based on 2,250,000 tons of U_3O_8 (Table 2-7) and 130 tons consumed per 6.6 billion kilowatt-hours.

The End of the Fossil Fuels

We put all these estimates together in Table 5-6 for the United States and in Table 5-7 for the world. None of these estimated times is long when compared to our own lifetimes (except for domestic coal). We want, however, to emphasize again that these are not predictions; what they show are the lifetimes *if* the past rates of consumption continue. The "lily pad" calculation drives home the fact that doubling of consumption at a fixed rate cannot continue for very long. Even coal, of which we consumed only 2/100, or 2 percent, of the reserves in the past 14 years, only lasts five 14-year doubling times. But after four doubling periods, 56 years from now, we would be using 32 times as much coal as we did in 1973, 18 billion tons per year. It is no wonder we predict that the supplies run out.

Uranium

We have limited ourselves so far in this chapter to the fossil fuels. As we saw in Chapter 2, however, uranium is not in great supply either, if we are restricted to the inefficient use characteristic of present-day reactors. It is of some interest, therefore, to make some similar estimate of the lifetime of this resource.

It makes little sense to project a constant rate, since we are just beginning to use this form of energy. The nuclear growth curve of Figure 4-20 shows a doubling time from 1970 until the early 1980s of about three years. In the three years from 1970 to 1972, we produced 120.9 billion kilowatt-hours (B kw-hrs) of electricity from nuclear reactors. Using a previous estimate (from Chapter 2), that 130 tons of U_3O_8 are the equivalent of 6.6 B kw-hrs of electric energy, we can calculate that 2,380 tons of uranium ore were needed to fuel this three-year period. This is about 1/1,000 of the total supply of under-$10 U_3O_8 (including the "by-product" uranium) of Table 2-7. Using the "lily pad" calculation, we find that the total of 2,250,000 tons will last through nine doubling periods, or 27 years, until 1999.

TABLE 5-7
Resource Lifetimes, World

Resource	Lifetime (years)	Assumed Doubling Time (years)
Oil	35	9
Natural Gas	45	9

We must again caution the reader against taking this as a prediction. We have assumed a very steep rate of growth (the doubling time for nuclear energy in Figure 4-20 remains at three years only for the 15-year period from 1965 to 1980). As the rate slackens, the lifetime of the fuel lengthens. We have also used the present reactor efficiency, and it is not unrealistic to expect some improvement in the kw-hr per ton figure.

The result of this calculation can be interpreted in two different ways. Twenty-seven years is a short time to be looking to the end of inexpensive uranium fuel. It is, however, a period of time long enough to allow some hope that a new energy source, solar generated electricity or fusion, for instance, might have reached a stage of development that would allow it to take up the task of producing electricity.

Finally, we must remind you that this calculation assumed that the reactors were fueled with fresh U_3O_8 each time. If the plutonium 239 that is generated in the fuel rods (see Technical Appendix 6 for discussion) is recycled, this lifetime also is lengthened.

Summary

In this chapter we focused our attention on the supply aspect of the energy picture. We reviewed the 1973 supply pattern with particular emphasis on imports of gas and oil, and then looked at the predictions of the National Petroleum Council for the years 1970-1985. This report estimates domestic supplies obtainable under four Supply Cases, whose assumptions ranged from the optimistic Case I: increased exploration and discovery of oil and gas (including offshore and Alaskan), minimum interference from the environmentalists, etc., to the pessimistic Case IV: decreasing domestic discovery, environmental constraints, etc. Although all estimates are for increased dependence on foreign oil in 1975 (40 percent to be imported), under the assumptions of the optimistic case we are self-sufficient by 1985. In the pessimistic Case IV we will still import 57 percent of our oil in 1985.

We examined, also, financial and other costs of the various supply cases; the optimistic case required a maximum in capital investment, around $550 billion, and the pessimistic Case IV projected the greatest balance of trade deficit, $32 billion in 1985. We looked at other requirements, in particular the tankers and deepwater ports needed for this increasing reliance on foreign oil. All of these costs will be reflected in increased energy prices; and we examined the record and projections in this area.

In the final section we examined resource lifetimes by taking the data on the sizes of the pertinent stockpiles that were given in Chapter 2 and applying to them the predictions of growing demand obtained in Chapter 4. Although the projections varied by a few tens-of-years, we showed that even the huge stockpile of coal can only stand five or six doublings of our present rate of consumption.

Chapter 5 has in it a description not only of the effects of accelerating demand, but a suggestion that one of the effects — cost — will break this acceleration. "Nature abhors an exponential" is, if not a law, a good rule of thumb, and the increased price is one of the signals that tells us that consumption must and will be slowed.

CHAPTER 6
New Flames from Old Fuels

New Flames from Old Fuels

In Chapter 5 we focused our attention on the supply-and-demand picture of the next decade, 1975 to 1985. What we saw, except for the hoped for maturing of nuclear energy, was essentially a scaled-up version of the past decade. Although the fossil fuels are only expected to contribute a little over 80 percent of the total energy in 1985, as against 95 percent in 1973, we will, in all likelihood, actually burn more of them in 1985 than we did in 1973.

By 1985, however, we can hope to see the beginning of change. We should be deep into research on some of the new energy sources described in Chapter 7. We should also be entering the developmental phase of some technological advances that will help us get more and cleaner energy from the fossil fuels. It is on these technological advances that this chapter focuses. We will look at developing techniques for getting different forms and cleaner energy from coal, and at techniques for improving the energy conversion efficiency of fossil and nuclear fuels, including the direct conversion of chemical energy to electric energy in a fuel cell. Finally, we will look at the potential and problems of storing electric energy by separating water molecules into oxygen and hydrogen. First, coal.

Clean, Versatile Energy from Coal

Coal, the old-new fuel, is, as we have documented in previous chapters, beginning to regain some of the prominence it had in the 1920s and again in the 1940s. Much of this resurgence is due to its abundance; we can count on it for several decades. Coal, however, is a solid, and its energy can only be efficiently released by burning it in large, stationary furnaces. It cannot, in its present form, provide for that part of our energy consumption that demands piped energy — liquid or gaseous fuels of high energy density. At present, only oil or natural gas can give the kind of quick-starting, controllable, and clean fires that are needed in our mobile heat engines (cars, trucks, and trains) and in other specialized heating tasks.

In order to give coal versatility to match its abundance, several determined and relatively well-financed research and development efforts are now under way to produce gaseous and liquid fuels from coal. We will briefly describe the present state of some of these efforts and look at some intriguing designs for new power plant systems, "coalplexes," which could give more versatility.

Gas from Coal

Crude techniques for producing a fuel gas from coal have existed for hundreds of years. In fact, "coal gas," the volatile, combustible gas driven from coal in coke making, was used for street lighting in early-19th-century London and even in the United States long before natural gas became popular. This "coal gas" (or "fuel gas," as we will term it here) has a low energy density, producing only about 80 Calories per cubic foot as compared with the 250 Calories per cubic foot of natural gas. This low energy fuel gas will, no doubt, be produced in significant quantities by the commercial processes now under development. Since it can be used industrially, it may become an important fuel for electric power plants. It is also possible to produce a synthetic "natural" gas, SNG, from coal that is completely equivalent to natural gas. SNG, no doubt, will be used as utility fuel, too, but it may also become a replacement for natural gas as shortages and demand drive up the price of that fuel.

We can identify the major technical problem of coal gasification by looking at the composition of the raw material, coal, and the desired end product, methane. The typical grade of coal (bituminous coal) used in steam generation contains about 75 percent carbon (by weight), 5 percent hydrogen, and 20 percent undesirable materials — minerals (which are left as ash) and sulfur (which creates the sulfur oxides of smog). Natural gas, on the other hand, is almost pure methane, CH_4, which is 75 percent carbon and 25 percent hydrogen. To create methane gas from coal requires that a considerable amount of hydrogen be added or that some of the carbon be rejected. With either choice (and a combination of both are used), the sulfur and minerals must be taken out if the SNG is to burn as cleanly as natural gas.

Six coal gasification schemes are now at various stages of development in this country. One of these, the Lurgi process, which was developed in Germany and is in commercial use in Europe, will be used in the first commercial development in this country. The El Paso Natural Gas Company is building a Lurgi gasification facility in northwestern New Mexico that will cost $500 or $600 million and produce 250 million cubic feet of gas from New Mexican coal.

Gas from the Lurgi process has lower heat value than natural gas (less than 100 as compared with 250 Calories per cubic foot) and will probably be used as a fuel for utility plants.

Of the several other projects designed for SNG production, perhaps the most advanced is the HYGAS process developed by the Institute of Gas Technology in Chicago. A diagram of the various steps of this process is shown in Figure 6-1. A reaction between coal (carbon) and hydrogen takes place in the *hydrogasifier* at high temperature and pressure (1,400-1,600°F and 1,000 psi).* The hydrogen is formed in the *gasifier* by reacting coal with steam.** The gas from the hydrogasifier contains a high percentage of methane along with carbon monoxide and dioxide (CO and CO_2), water, hydrogen, and sulfur compounds. The impurities are removed in the *gas purification* system. A great advantage of coal gasification is that sulfur is removed as a gas, H_2S

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*The chemical formula of this is roughly $C + 2H_2 \rightarrow CH_4 + \text{heat}$.

**The chemical description is $C + H_2O + \text{heat} \rightarrow CO + H_2$.

(hydrogen sulfide, the "rotten egg" gas). Elemental sulfur can be reformed and its sale could reduce the cost of the SNG.

The final step, *methanation*, combines carbon monoxide and hydrogen (in the presence of a catalyst) to form more methane.

A HYGAS pilot plant at the Institute of Gas Technology produces 1.5 million cubic feet of pipeline quality gas per day from 75 tons per day of coal. Since the gas contains about 0.26 million (M) Calories per 1,000 feet^3 and the coal 6.1 M Calories per ton (Table 1-3), the efficiency of this gasification process is about 85 percent. Some energy from other sources is used and, therefore, the actual efficiency of gasification is nearer to 65 or 70 percent. Some of the coal energy is lost, but since we lose the smog-producing sulfur and the ashes, also, it is a good bargain.

It has been suggested by Squires[1] that it is not necessary to wait for these advanced SNG plants to begin to supplement our gas supplies with coal. The lower-heat-content fuel gas can be made much more simply in small plants and could rather quickly (his estimate is two years) replace natural gas in small industrial plants, and in providing heat for brick and glass manufacture, etc. This replacement, and even the utilization of fuel gas in utility plants, will depend on its price competitiveness with natural gas.

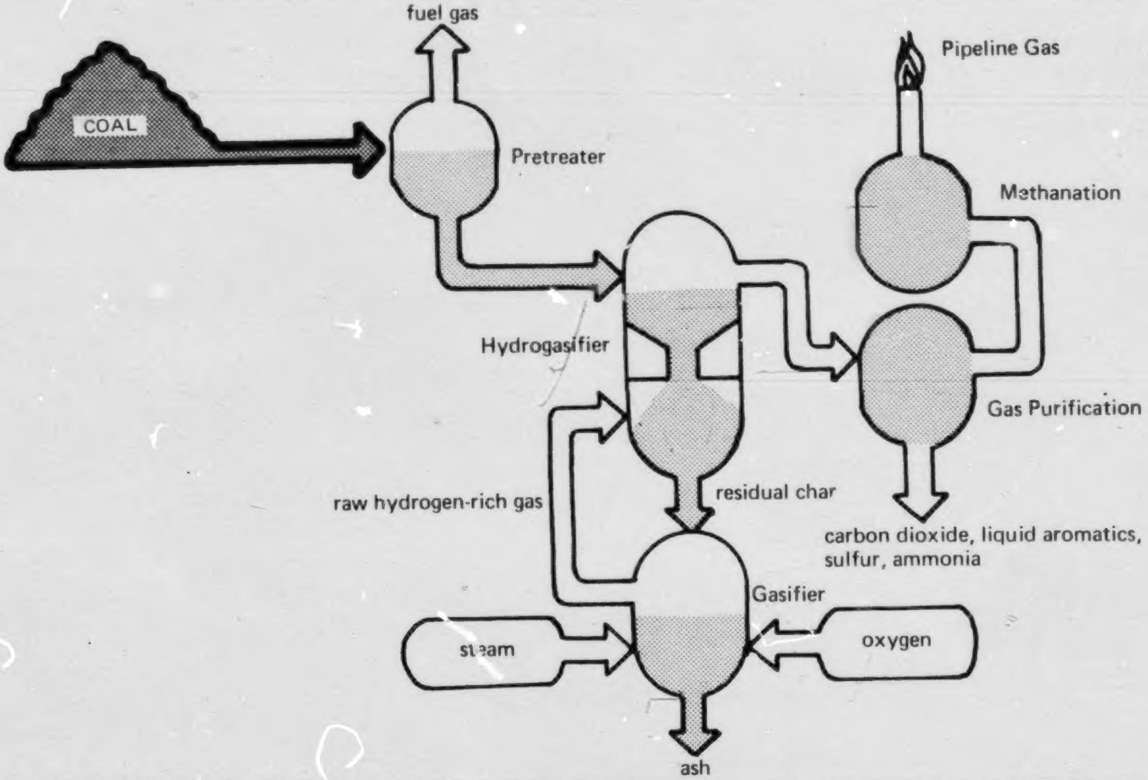
Oil from Coal

It is also possible to make oil from coal, as was demonstrated by the Germans during World War II, but it is not presently economical. Although a typical gasoline molecule, such as heptane (C_7H_{16}), has a smaller percentage of hydrogen than methane (15 percent instead of 25 percent), it is a more complicated molecule and more difficult to form.

There are continuing efforts under way in research laboratories aimed at producing gasoline and light oils from coal. The first large-scale contribution of liquid fuel from coal, however, will likely be a heavy, low-sulfur fuel oil for use in electric utility furnaces. Typical of these research and development efforts are those producing SRC, "solvent refined coal."

SRC is a solid, like tar or pitch, that can be melted (at 180°C) and, therefore, shipped by tank car or pipeline and used as liquid fuel. SRC is formed by dissolving coal in a solvent (which may, in fact, be an oil derived from the coal itself) at high temperature and pressure. Since the carbon is now in a liquid form, it is easy to filter out impurities, such as ash and sulfur. In some processes hydrogen is added so that lighter molecules will be formed and, most important, H_2S will be formed, which expedites removal of the sulfur impurities.

FIGURE 6-1
HYGAS Coal Gasification Process



Source: Institute of Gas Technology (Chicago, Illinois).

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[1] A. Squires, "Clean Fuels from Coal Gasification," **Science 184,** 340, April 19, 1974.

The cleaned liquid is then heated to evaporate the solvent (and the light oils and gases) from the coal; the resulting hard, brittle and high-energy-content residue, the SRC, can be shipped. The solvent and the hydrogen from H_2S are recycled. The overall efficiency is expected to be 67 percent; that is, 67 percent of the energy content of the coal plus the hydrogen containing natural gas is retained by the SRC and the distilled oils.

The main advantage of SRC is that it produces a uniform, energy-rich, ash-free, low-sulfur fuel from any kind of coal. The energy value of SRC is 8 M Calories per ton as against 5 to 6.5 M Calories per ton for coals. The ash level may be as low as 1 percent and the sulfur content 1 percent or less. The SRC process will probably find its most competitive application to the high-ash-content, low-sulfur, and low-energy-content Western coals. A 50-ton-per-day pilot plant, supported by the Office of Coal Research, is nearing completion near Tacoma, Washington; a similar plant, funded privately, is planned for Alabama.

Generally, liquifaction of coal lags well behind gasification in its development, and unless large amounts of money are made available for R & D, it will not make a significant contribution to the energy problem for the next two decades. The National Petroleum Council (NPC) optimistic Case I forecast is for about 680,000 barrels (bbls) per day in 1985 (4 percent of the anticipated domestic oil production of 16.89 M bbls) and the pessimistic Case IV assumption is for no coal-derived oil in 1985.

Cost

The cost of the coal-derived liquid or gaseous fuels depends, of course, on the cost of coal. In Table 6-1 we give expected costs of these three fuels for two different coal prices (which are representative of the high-priced coal from Eastern underground mines and the lower-priced coal from Western surface mines). As a reference against which to judge these prices, oil at $7.00 per barrel (its approximate current price) can provide a million Calories at about $4.70, while at $11.00 per barrel a million Calories would cost $7.30. Liquified natural gas, on the other hand, is projected to sell for $6 to $8 per million Calories. It would appear that synthetic fuels will soon be at least marginally competitive.

TABLE 6-1

Comparative Costs of Coal-Derived Synthetic Fuels (in dollars per M Calorie (a))

Utility Gas	Eastern Coal(d) $12 per ton	Western Coal(d) $6 per ton
Utility gas (fuel gas)	5.00	3.60
Liquid Fuel (SRC)(b)	8.00	6.80
Pipeline Gas (SNG)(c)	10.80	9.60

Source: "Project Independence Report," Federal Energy Administration, November 1974, pg. 139.

(a)M Calories = million Calories.

(b)SRC = solvent refined coal.

(c)SNG = synthetic natural gas.

(d)The cost of synthetic fuels derived from Western coal relative to that from Eastern coal is higher than might be anticipated by the relative costs of Western and Eastern coal. This results from differing transportation costs from the plants, which must be near the source of coal, to the consuming region.

"Coalplexes" in Our Future?

Some coal engineers look to a future in which coal conversion plants will serve several different purposes and produce different products. One of the most articulate and farsighted spokesmen for this view is A. Squires of City College, of the City University of New York (whom we have quoted earlier).

He proposes a coal treatment complex, a "coalplex," that has as its main goals sulfur and ash removal before combustion — clean fuel — and much higher efficiency of thermal to mechanical energy conversion — cheap power. The important ingredients in the accomplishment of these goals are a new furnace-boiler design, the "fluidized bed," to replace the present PF boilers, and the addition of a gas turbine "topping cycle." We will define both these terms in what follows.

In the PF (for pulverized fuel) firing, which is the present system, powdered coal is injected by an air blast and burned, the ashes settling through a grate. Modern furnaces of this type are huge; the 1,000 megawatt (MW) Ravenswood Station of New York City's Con Edison has two firing chambers 34 by 64 feet by 138 feet high.

These PF boilers are simple and relatively efficient. With fairly simple add-on equipment, they also can handle the ash and soot problem, the "particulate" emissions we discussed in Chapter 3, Volume I. So far, however, no economically viable method of removing the sulfur oxides from the stack exhaust has been invented. Squires is among a growing number of coal engineers who stress the advantages of a different type of furnace, the "fluidized bed." Among its advantages is precombustion removal of sulfur.

In this combustion system, crushed coal is buoyed up, floated by a blast of high-pressure air from below. It burns in the air blast, reaching a temperature of 2,000°F, at which point the ash has the fortunate property of sticking to itself, "agglomerating," and then dropping down and out the grate.

The hot gases rise above the shallow region where the coal is burning and drive volatile gases out of the coal floating in this area. This degassed coal, char, is now more nearly pure carbon, and heavier. It sinks down into the combustion region and burns. If steam is added to these hot gases, hydrogen, liberated from the water molecule, will combine with the sulfur to make hydrogen sulfide, H_2S. The H_2S can then be filtered or otherwise removed from the fuel gas.

The fuel gas that is produced is an important fuel for the "topping cycle." This is a cycle that operates at very high input temperatures (T_{in} of the efficiency equation of Chapter 3) and exhausts its working fluid at a temperature (T_{out}) that is still high. Steam turbines are now operating at about as high a temperature (1,000°F) as is realistic. The fuel gas from the fluidized bed we have just described, however, can be burned and injected into a gas turbine that can operate at 2,000°F. and above. The gas turbine can extract mechanical energy from the gas and the still-hot exhaust gas can then create steam for a conventional steam turbine. An overall efficiency of 50 percent may be obtained, giving more energy and less waste heat to be disposed of in the environment.

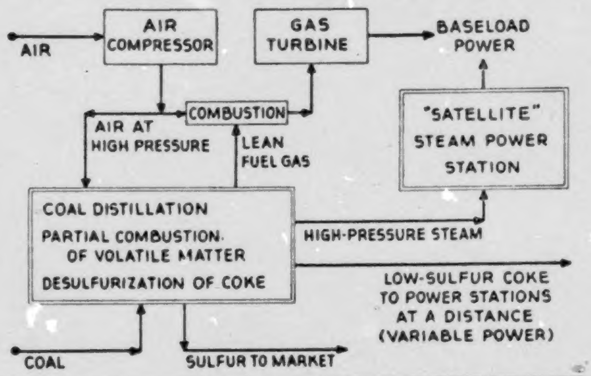
This "combined cycle" electric generating plant would be the heart of the coalplex. Variations on it are possible. In the "topping cycle," the gas turbine might be replaced by the MHD generator, which we will discuss in the following section. It is also possible to add, as a "bottoming cycle," a turbine run by the expansion of a fluid with a boiling point lower than water and thus extract energy from the exhausted steam. Efficiencies as high as 60 percent may be reached in such a combined cycle plant.

The overall coalplex operation is shown in the flow diagram of Figure 6-2. In the main chamber a fuel gas is distilled from the coal, part of it is combusted there to provide heat and part goes to run the gas turbine. The desulfurization also takes place there. The heat produced in this chamber creates steam for a steam power plant that also receives a contribution from the gas turbine exhaust. The products, in addition to electric power, are sulfur and a low-sulfur fuel, coke or "char," which, with its high-energy and low-sulfur content, is worth shipping to other distant power plants.

For most economical operation these large coalplexes would be located at the mine. One of the scale being described here might process 13 M tons of coal a year, produce 1,000 Mw of electric power itself and provide sulfur-free fuel for another 5,000 Mw as well as 400,000 tons of sulfur. Squires further projects these evolutionary steps:

1. The first coalplexes would be justified simply for their economy in dealing with sulfur.
2. Later, modifications would "cream off" limited amounts of pipeline gas and liquids from volatile matter. Simplicities in the processing of volatile matter would result from opportunities to throw off high-level waste heat to steam for power.

FIGURE 6-2
Flow Diagram for a Coalplex



3. As time passed, further modifications would expand production of gas or liquid.
4. Ultimately, in an economy powered principally by breeder reactors, a coalplex would evolve for which power might be a relatively minor byproduct, and fixed carbon would be shipped mainly for metallurgical or electrochemical use.

This is, in many ways, an attractive scenario. It offers hope of improving the energy situation as well as abating air and thermal pollution.

It appears likely that coal gasification plants will begin limited operation in the 1980s. Whether liquid fuels or the multipurpose coalplexes will become a reality is more problematical and depends to a large extent on our commitment to nuclear energy. All three of these techniques remove much of the pollution coal releases at the consumption end of the energy flow. At the production end, however, the problems described in Chapter 2, Volume I, remain.

More Efficient Conversions: Other Techniques

The new combustion techniques and the topping cycle we have just described offer hope for higher efficiencies in the conversion of the chemical energy of coal to the highly desired intermediate form, electricity. There are other techniques using other fuels as well as coal that have the same goal. One with an impressive name is the magnetohydrodynamic (MHD) generator.

This device is designed to shortcut some of the conversion steps in the long pathway from chemical energy to electric energy. A schematic diagram of a MHD generator is shown in Figure 6-3. The fuel (which could be coal, oil, or gas) is burned and the hot combustion gases enter from the right. They are *ionized,* inside the generator, that is, the electrons are separated from the rest of the atom. When this ionized gas enters the magnetic field region at the left end, the electrons are bent by the field in one direction, strike the collectors in the wall, and the now positively charged atoms (some of whose electrons were removed) are bent and collected on the opposite wall. Since one set of collectors is collecting positive charges and the other set negative charges, connecting the two sides through some load (any device that uses electric energy) will cause current to flow and electric energy to be converted to work or heat. The MHD generator, thus, converts thermal energy directly to electric energy and bypasses the steam turbine and generator steps of a conventional system.

The MHD generator is only 20 to 30 percent efficient. It can, however, be added on as a topping cycle and the hot exhaust gas used to power a conventional steam turbine. Overall efficiencies may be as high as 50 to 60 percent.

The United States has lagged in MHD development. England, France, Germany, Japan, and Poland all have more ambitious programs under way. The U.S.S.R. has the most advanced program — a 75 Mw unit fueled by natural gas is being tested.

There are several difficult problems to be solved before MHD generators come into routine use. There is serious corrosion of the duct and the electrode at the high temperatures, and the task of providing a large magnetic field near such a high-temperature gas is also challenging. Since it has no moving parts, however, it should, when perfected, be an almost trouble-free addition to electric power generators.

Bottoming Cycles

We have discussed two topping cycles that use otherwise wasted high-temperature heat energy. Heat energy wasted at the other end could be converted in a bottoming cycle.

The steam exhausted from a steam turbine may be 300 to 500°F and thus have considerable heat energy left in it. To use this in a heat engine, however, we need a fluid that boils at a temperature well below water's 212°F. Ammonia, for instance, boils (at atmospheric pressure) at −92°F. The exhausted steam can vaporize such a low-boiling-point liquid, cause it to expand, and this high-pressure vapor can then turn a small turbine to generate additional electricity. The overall efficiency of the combination is still given by

$$E = \frac{(1 - T_{out})}{T_{in}} \times 100$$

but with topping and bottoming cycles T_{in} can be very high and T_{out} can be as low as the temperature of the air, making for higher efficiencies.

The bottoming cycles are not only of use in steam power plants but also will be useful in opening up some of the low-temperature geothermal reservoirs to exploitation and will be essential to the solar seapower generator we will discuss in the next chapter.

Money

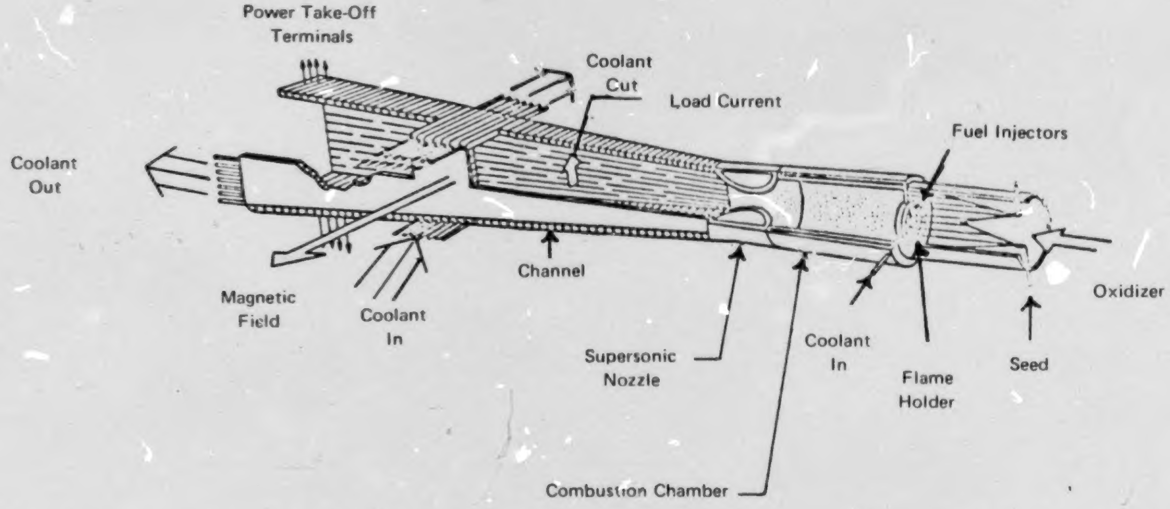
In the previous sections we outlined several of the important contributions coal research can make to the needed development of gaseous and liquid fuels and to a cleaner environment. There is a certain sense of frustration in making this review, for much that is reported is not really new. The knowledge of the techniques for these conversions has existed for a long time; what has been missing has been R & D money. We will examine overall R & D funding elsewhere. The important comparison is between research on coal and on nuclear energy. Expenditures for coal research and for nuclear fission research are compared for the years 1969 to 1975 in Table 6-2. Only in the 1975 projections (and such projections can't always come to pass) does coal research support compare with support for the nuclear alternative.

With this less-than-gracious introduction, let us now look at the promise of nuclear fission.

More Energy from the Nucleus

The Light Water Reactor, LWR, which is being rapidly phased into our electric generating network, is not very efficient. (We discuss these reactors and describe their fuel and operation in Technical Appendix 6.) Present efficiencies are about 30 percent, less than the 40 percent efficiency of the best fossil-fuel-fired steam turbine plants. For fuel the LWR uses "enriched" uranium containing 2 to 4 percent U^{235}. We saw in Chapter 2 that the stockpile of this fuel is not impressively large.

FIGURE 6-3
A MHD Generator



Source: Avco Everett Research Laboratory, Inc., Everett, Massachusetts.

On the drawing boards and in the laboratories of ERDA and their contractors a most interesting (and controversial) new type of reactor is undergoing final design and testing. This breeder reactor is expected to be demonstrated in the 1980s. When it begins large-scale operation, targeted for the 1990s, it will greatly increase the amount of energy available from the uranium stockpiles. The name of this reactor comes from its ability to create new fissionable fuel in addition to providing energy. As we describe in Technical Appendix 6, one of the important by-products of the fissioning (splitting) of a uranium nucleus is the neutron (a basic building block of the nucleus). It is these neutrons that strike other fissile uranium nuclei and cause them to split and thus keep the chain reaction going. The LWR fuel, U^{235}, is rare, only 0.7% of natural uranium. The major component is U^{238}, which is not fissionable by these by-product neutrons. The neutrons from the U^{235} splitting, however, can be captured by U^{238} and initiate a series of nuclear reactions that produce plutonium (Pu^{239}), a fissionable nucleus that can be used as a reactor fuel.

The measure of the effectiveness of a breeder reactor is its "breeding ratio," the ratio of the amount of Pu^{239} produced to the fuel used. If this is greater than 1, then the breeder will produce more fuel than it consumes.

The LMFBR

The breeder reactor that is to be demonstrated in 1980 is called a Liquid Metal Fast Breeder Reactor, LMFBR. To be the prototype of the next generation of nuclear plants, it could, using the presently available stocks of uranium, provide us with electric power for hundreds, perhaps thousands, of years. In spite of this promise, its entry into the energy picture has not been universally acclaimed. It will bring us, in addition to more energy, a number of perplexing problems.

First, the good news: The breeding ratio of the demonstration breeder is expected to be about 1.2; it will create 20 percent more fuel than it burns. The larger plants that will follow it may have breeding ratios as high as 1.4 or 1.5. In these plants the "doubling time," the time that it takes to produce enough fuel for another reactor, will be about 10 years. It is this rapid doubling that makes it attractive; it doubles fuel about as fast as our consumption of electric energy is doubling.

The LMFBR can create fissile fuel from the leftover U^{238} that accompanies fuel preparation and can, therefore, be brought into operation without further mining of uranium. Since it can use 50 to 70 percent of the available uranium as fuel rather than the 2 percent or less used in LWR's, it increases the size of the uranium stockpile (see Table 2-7) by almost a factor of 50. In fact, it will use such a small quantity of uranium as fuel, 1½ tons per year as against 130 tons per year in the LWR, that the price of the electricity it will produce will not be sensitive to the price of uranium. Even if uranium goes to $100 per pound (it is now about $10 per pound), the price of breeder reactor-produced electricity would change hardly at all. (The price of electricity produced by a LWR would increase by 75 percent.)

So insensitive is the LMFBR to the price of uranium, it is conceivable that it can be made to operate economically on much lower-grade uranium ores, such as granite. With its uranium content made fissionable in a breeder, a ton of granite has more energy potential than a ton of coal.

The hope held out to us by proponents of the LMFBR is that of plentiful, inexpensive electricity. This reactor, it is claimed, not only will produce cheap electricity itself but will provide a growing stockpile of Pu^{239} that can be used in the LWRs to reduce their fuel costs.

That's the good news, but it is balanced by bad news. Many problems await solution before the LMFBRs can join the utility team. They will be very expensive, requiring large capital investment (the demonstration plant will have a capital cost at least twice that of the present-day LWRs). It is anticipated that they will be more difficult to control; there are other technical problems growing from their use of liquid sodium as a coolant. Perhaps the most serious reservations concern the Pu^{239} they produce. This artificially produced material is not only an extremely dangerous radioactive poison, it is also the

TABLE 6-2
Federal Energy Funding for Research and Development, 1969-1975 (in millions of dollars)

	FY 1969	1970	1971	1972	1973	1974*	1975**
Coal Resource Development	23.3	30.4	49.0	76.8	85.1	164.4	426.7
Nuclear Fission Breeder Reactors	132.5	144.3	167.9	237.4	253.7	357.3	473.4
Other Civilian Nuclear Power	144.6	109.1	97.7	90.7	152.8	173.2	251.7
Total Fission	**277.1**	**253.4**	**265.6**	**328.1**	**406.5**	**530.5**	**725.1**

Source: Table 5, "Exploring Energy Choices," Energy Policy Project of the Ford Foundation, Washington, D.C., 1974.

* Estimated
**Proposed

raw material for atom bombs. We discuss some of these problems in Chapters 3 and 4 of Volume I.

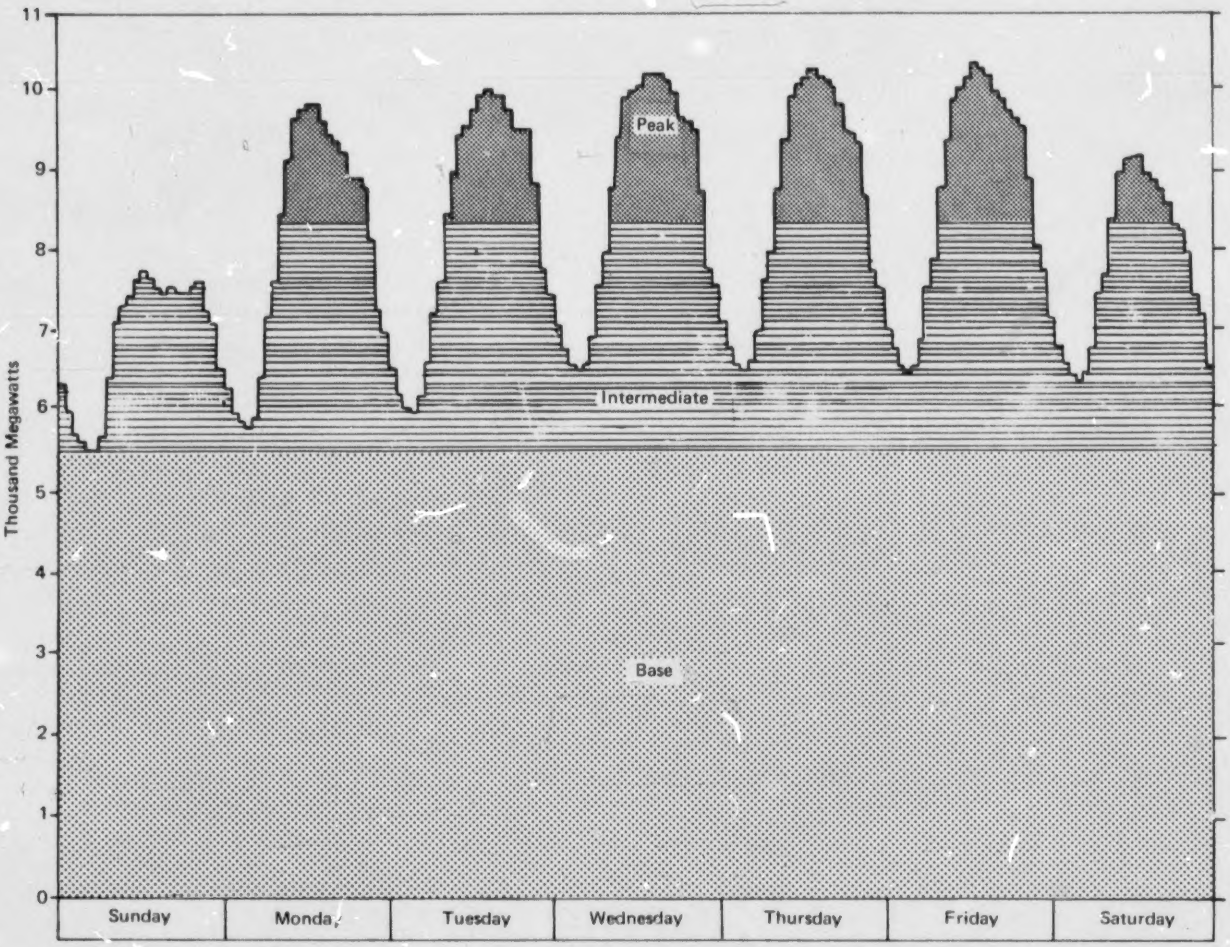
There is considerable opposition to the breeder reactor and it is one of the major issues in the "energy debate" under way in this country. To make a judgment for or against the breeder, however, would take us well beyond the physical description we have given here, or even the environmental and human hazards we describe in the first volume. What provides the thrust to its development is this country's increasing need for electric energy and the continuing depletion of the fuels we have historically used to generate it. Alternative sources of energy, whose promise and problems we examine in Chapter 7, are, therefore, of particular pertinence.

The Ups and Downs of Electric Demand

Electricity, in many ways the "All-American Energy," is nonetheless flawed. We have examined one of these flaws, the inefficiency of the heat engines that turn the electric generators. The most serious flaw, however, stems from its kinetic nature. It is energy on the fly, difficult to store, and must be used at once.

The kinetic nature of electricity creates other difficulties. It contributes to inefficiency. Since electricity cannot be effectively stored, it must be generated on demand (we will discuss some of the small-scale storage attempts — batteries and pumped storage — in the following section). This means that the utility plant must have sufficient generating capacity to meet maximum demand and, therefore, that generating capacity must stand idle when demand falls below peak level. A glimpse at the problem faced by an electric utility is provided by Figure 6-4, which shows the typical weekly fluctuation in demand. In this illustration we see not only a day to night change of 40 percent but, for instance, a 25 percent difference between the Wednesday and Sunday peaks. If we looked at Figure 6-4 with a magnifying glass, we would see that the demand is constantly fluctuating.

FIGURE 6-4
Electric Power Weekly Load Curve



Source: **The 1970 National Power Supply Part I**, Federal Power Commission, USGPO Washington, D.C., 1971, pg. I-7-5.

This fluctuating demand can only be met with a flexible generating system. The large steam-driven generators (coal-fired or nuclear) that provide 75 or 80 percent of the power are, however, not very flexible. They are designed to operate at maximum efficiency at maximum power output. And, as you can easily imagine, they are difficult to turn on and off quickly.

The large generators provide what is called the base load, the more or less constant amount of power that is always needed. To take care of the intermediate load, gas or oil-fired furnaces are used. Controlled by automatic equipment, they can be started or stopped quickly. The peak loads, then, are provided for by generators driven by diesel engines or gas turbines. The hydroelectric plants, in particular the "pumped storage" systems we describe below, also are used to supply peak loads, as they, too, can be quickly turned on and off.

The efficiencies of these various reserve units vary. The diesels and gas turbines used to meet peak demand are the least efficient, 20 to 30 percent at best, and, in addition, they burn costly fuel. For these reasons peak electricity is expensive. The price of electricity could be lowered if the peaks were smoothed out and the valleys filled in; if, in other words, most of the load could be carried by the big, efficient and inexpensively fueled base-load generators.

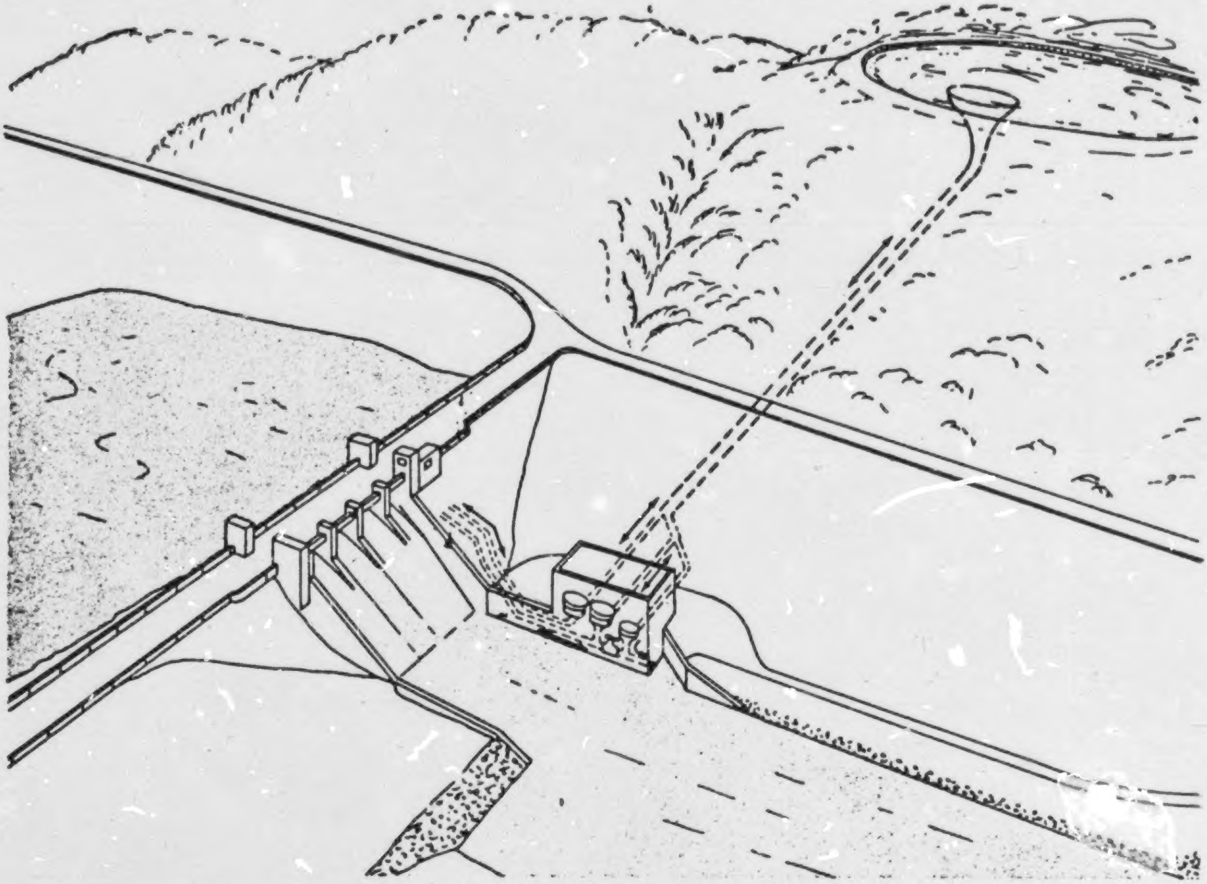
Storing Electricity

One way to fill in the peaks is to store electricity. (We mention briefly in Chapter 5, Volume I, some changes in the rate structure that might have similar effects.) At present, only two methods of storing electric energy are available to us. Batteries are used for the storage of small amounts of energy, and "pumped storage" plants are being built to provide larger storage capacity.

Considerable research is under way to improve batteries. The search is on for new battery materials that will have a higher energy density — that is, will store more kw-hr per pound — and for batteries that can be charged and recharged many times. Such batteries of the future could be useful for "off-peak" power storage (power generated during low demand) and could make a non-polluting electric automobile possible.

Pumped storage: Figure 6-5 shows a sketch of a pumped storage plant. This storage technique has been

FIGURE 6-5
Sketch of the Kinzua (Pennsylvania) Pumped Storage Project



Source: **The 1970 National Power Survey Part I,** Federal Power Commission, USGPO, Washington, D.C., 1971, pg. 1-7-7.

made possible by the perfecting of reversible pump-turbines. These devices can be run as turbines when water is flowing through them and then can be quickly reversed to pump the water back uphill, storing gravitational energy. The water is pumped up into the reservoir during off-peak times when there is no demand for the extra power available from the big generators. At times of peak demand, the water runs back down through the turbines to turn the generators. Even though these reversible turbines are only 66 percent efficient — one-third of the energy is lost in this storage step — the difference between the cost of peak and off-peak power makes them practical. This form of storage is expected to grow rapidly in the next decade.

Hydrogen as Intermediate Energy

The need to store electric energy economically, which will become more and more acute as we turn to nuclear power plants, has caused a great deal of interest in the potential of hydrogen for intermediate energy storage and for use as a secondary fuel.

The storage technique is simple. Hydrogen can be separated from the oxygen in the water molecule by forcing an electric current through water. This is the process of electrolysis, which most of us have seen demonstrated in high school chemistry. It takes energy to separate the hydrogen and oxygen, and that energy can be reclaimed by burning the hydrogen. In fact, this is one of the exciting additional advantages of hydrogen. Burning it, combining it with oxygen (which is the definition of burning), produces water again; it is unpolluting combustion.

Hydrogen has a second important advantage as an intermediate form of energy. As we show in Figure 3-5, it is three to five times less expensive to ship energy as a gas in a pipeline than as electricity in a high-voltage transmission line. Not only is electric energy lost in transmission, but the transmission involves expensive technology and uses expensive land for rights-of-way.

What is being suggested, therefore, is that large quantities of electricity could be generated by huge generating plants used to produce hydrogen from water, and the hydrogen could then be stored, shipped, and used as needed.

The end uses available from hydrogen are almost as varied as from electricity itself. Some idea of the variety is given in Figure 6-6. It can be burned to produce thermal energy to provide heat for homes, industry, etc. It may even become economical to burn it to regenerate electricity. It could be used as a fuel for cars, and even airplanes. However, gaseous hydrogen, although it has a large heat value (three times as much per pound as gasoline), takes up too much space. It is readily absorbed in some metals, and in future automobile tanks may be stored in metallic granules from which it can be released by heating when needed.

Hydrogen is also potentially useful in many chemical and other industrial processes. The availability of plentiful cheap hydrogen would make coal liquifaction and gasification much more economical, for instance. The by-product oxygen could also be extremely useful. The most important end use of hydrogen, however, may turn out to be its attractiveness as a fuel for the "fuel cell," another highly promising product of technology that we discuss in the last section of this chapter.

We are not able, however, to turn immediately to a hydrogen-fueled economy. It has its drawbacks. Some of these are technical. Hydrogen is very light gas (it is the smallest atom), and this makes it difficult to store and pipe. It diffuses into metals and this weakens them. It is explosive (but so is gasoline).

Its biggest drawback at present is price. One estimate is that hydrogen will cost \$6 to \$10 per M Calories if electricity costs 4 to 7 cents per kw-hr. Natural gas now costs \$1 to \$4 per M Calories, so we must await another technological breakthrough to lower the price of hydrogen before it becomes competitive. There is considerable research under way at present not only aimed at increasing the efficiency of electrolysis, but also at discovering other ways to disassociate water. Here is one of the areas into which more research money should be channeled to insure that economical hydrogen will be possible when the scarcity of natural gas and the availability of cheap electricity makes its use feasible.

Hydrogen storage will not only be advantageous in connection with the fossil-fuel-fired and nuclear generators, but also for some of the exotic electric generators of the future. This will be particularly true if we turn to some of the continuous but erratic sources — the wind or solar energy — for our electricity. The most intriguing future possibility for the conversion of hydrogen, however, is in the fuel cell and we shall discuss that device next.

A Fuel Cell in Your Future?

One of the most exciting products of energy technology is the fuel cell; a device that generates electric energy directly from chemical energy. It is somewhat like a battery in this regard, but differs significantly in that the chemical energy, rather than being stored, is fed into it continuously.

The fuel cell operates, in a sense, as a slowed-down combustion reaction, as slow-motion burning. In combustion, electrons are removed from the fuel molecules ("oxidizing" them in chemical terms) and are attached to the oxidizer molecule ("reducing" them). Four Calories of energy per kilogram are released in the reaction. In chemical symbols the burning of hydrogen is written:

$$H_2 + O \rightarrow H_2^{++}O^{--} + \text{energy}$$

where the +'s indicate that each hydrogen atom has given up an electron and the −'s indicate that the oxygen atom has attached them.

When hydrogen burns in air (or oxygen), the reaction takes place very rapidly and the energy is released explosively as heat. In the fuel cell the same transfer of electrons takes place, but the fuel and the oxidizer molecules are physically separated and the electrons must travel around an electric circuit, creating an electric current, and doing work. The same 4 Calories per kilogram of hydrogen are released in this controlled manner.

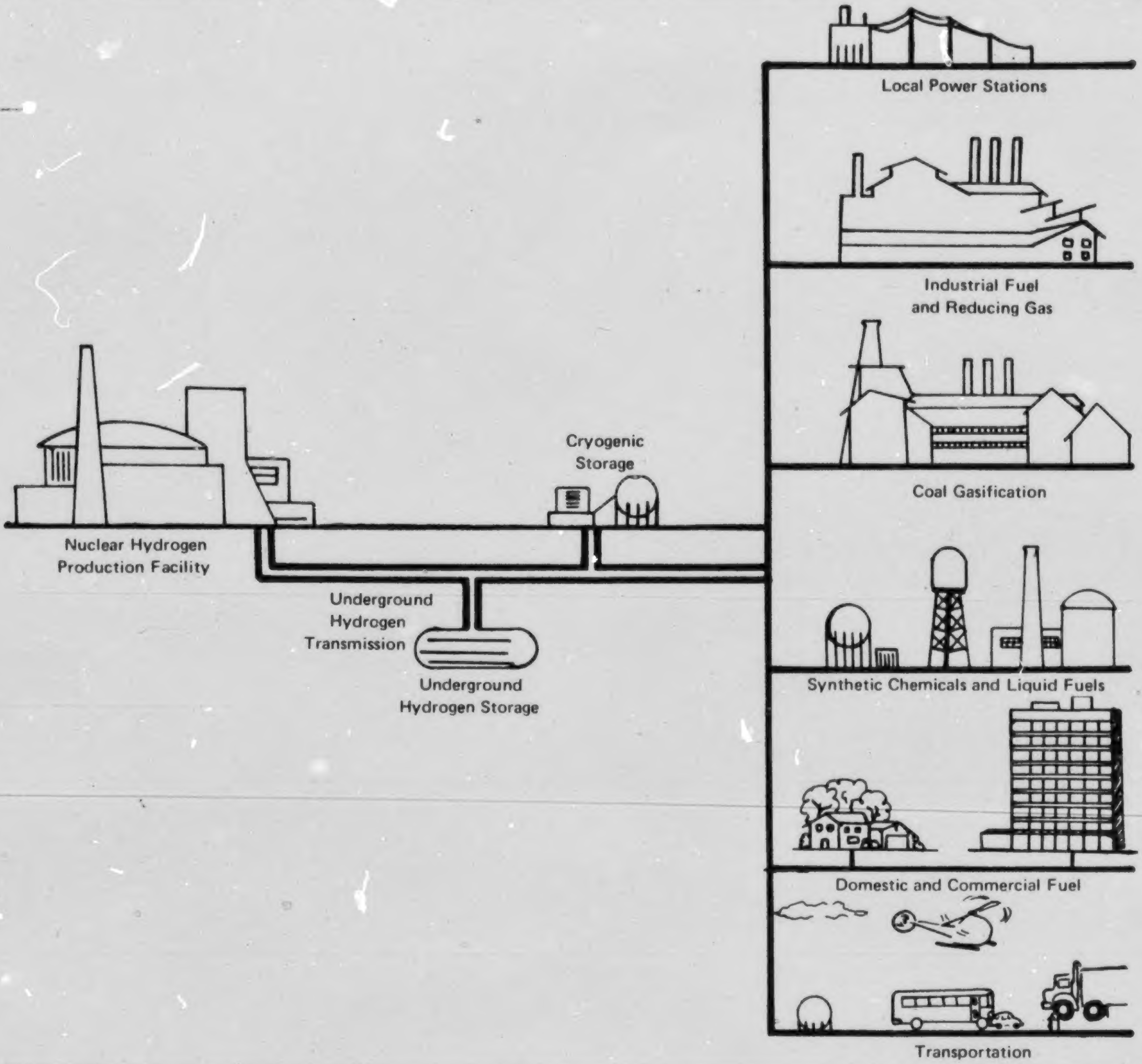
A schematic drawing of a fuel cell is shown in Figure 6-7. Its structure is similar to a battery. There are an anode and a cathode; the fuel molecule (usually hydrogen) enters and diffuses through the anode and an electron is stripped from it. At the cathode, the electrons that flow around the circuit from the anode are picked up by the oxygen molecules which, with water, create OH^- ions (that is, an oxygen atom joined to a hydrogen atom with an extra electron attached). The OH^- ions then migrate through the electrolyte and join with the H^+ atoms from the anode to form water, the sole residue of the hydrogen oxygen fuel cell.

A single fuel cell is not a very impressive power source. It can produce 100 to 200-thousandths of an ampere of current at about 1 volt: this is 0.1 to 0.2 watts of power. But such a fuel cell is very small and many of them can be connected.in sequence to build up power levels of 100 Mw, or greater. Their size is one of their significant advantages; a 1 Mw unit, it is estimated, would occupy the volume of an 8-foot cube.

Operating on pure hydrogen and oxygen, a fuel cell is quite efficient — 70 to 80 percent in the best cells. The cells being developed at present must obtain hydrogen from some other fuel, natural gas, oil, wood alcohol, etc. Since energy is needed to separate the hydrogen from the fuel molecules, the actual efficiencies are nearer 40 to 50 percent.

The advantages of fuel cells over other forms of gen-

FIGURE 6-6
Uses of Hydrogen as an Intermediate Form of Energy


Local Power Stations
Industrial Fuel and Reducing Gas
Coal Gasification
Cryogenic Storage
Nuclear Hydrogen Production Facility
Underground Hydrogen Transmission
Underground Hydrogen Storage
Synthetic Chemicals and Liquid Fuels
Domestic and Commercial Fuel
Transportation

eration are numerous. They are competitive in efficiency. They are quiet. The only moving parts are fans and pumps. They pose no pollution threat since the waste products are carbon dioxide and water.

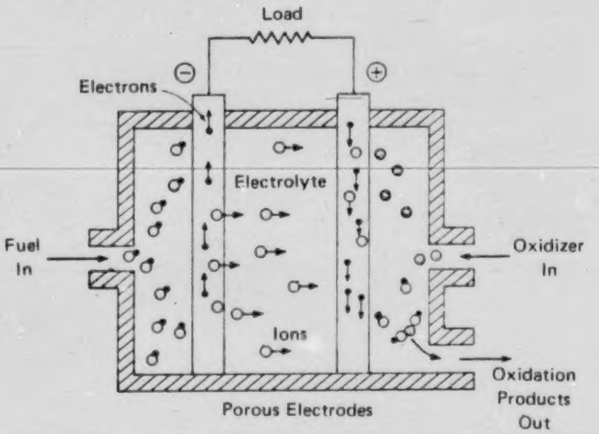
The fact that they can use gas as a fuel is a most interesting advantage. As we have said, it is three to five times less expensive to pipe energy in gaseous form as it is to transmit the same amount in the form of electricity. Thus, even though a modern fossil fuel generating plant may be as efficient as a fuel cell, the fact that the fuel cell can create electricity at the site from piped-in gas results in the fuel cell producing 10 to 25 percent more energy than the power plant delivers from the same amount of fuel.

The fuel cell is being developed for several applications. The goal of one $42-million program of Pratt and Whitney Aircraft and a group of utilities is to develop a 26 Mw hydrocarbon-air fuel cell generator for use at substations and load centers within existing electric systems. Such a device could give much more efficient and, therefore, inexpensive peak-power response than can the generators we discussed earlier.

A second program, also carried out by Pratt and Whitney for a group of gas utilities, is TARGET (Team to Advance Research on Gas Energy Transformation). The goal of this program is to develop small-capacity, 12.5 kw fuel cells for on-site conversion of natural gas to electricity in offices, small businesses, apartment buildings, schools, groups of residences, etc. TARGET has already tested this concept in 65 locations of this type and expects on-site fuel cells to be in service by the end of the decade.

The fuel cell proponents remind us that a considerable amount of natural gas is burned to generate electricity and point out the energy gains and benefit to the environment that on-site fuel cell conversion could bring. They also look ahead with great anticipation to the availability of hydrogen and the increased efficiency in conversion that could be obtained by putting back together, in a fuel cell, the hydrogen and oxygen originally separated by electrolysis at some huge, distant power plant. It is not an unattractive vision.

FIGURE 6-7
Schematic of a Fuel Cell



Summary

Many of the problems that beset us in these troubled 1970s seem to have been caused by a technology that runs ahead of its time, that has not been carefully preplanned and integrated into the global ecology. Because of this, some modern-day Luddites are turning away from future technology. We cannot turn back from technology, however. We cannot continue much longer to meet existing demand for energy with our present devices and techniques. To provide the growth required to allow all our citizens access to the comfort, convenience, and necessity that air-conditioners, freezers, dryers, etc. bring, we will need more energy, in particular, more electric energy. Part of this will be supplied by new energy converting devices.

Goals of the technological contributions examined in this chapter are: more efficient conversion of energy, more variety in energy forms, and less environmental damage. We looked at progress in five areas: (1) the conversion of coal into liquid and gaseous fuels, (2) topping and bottoming cycles to use the heat energy that is now wasted at the high-temperature and low-temperature ends of stationary heat engines, (3) the breeder reactor that promises new energy from our uranium stockpiles, (4) the need for improved storage techniques for electric energy and the separation of hydrogen from water, which may prove to be a very useful way to store such energy, and (5) the "fuel cell," which converts the chemical energy of gas directly into electric energy.

In a priority ranking, we would probably have to rank coal gasification and the fuel cell as offering the most exciting near term promise, followed by the controversial breeder reactor, and the multipurpose coal converting plants (the coalplex), which could create heat for electricity and new and clean gaseous and solid fuels.

Still in the "blue sky," but showing enormous promise, is the use of hydrogen as an intermediate form of energy. Hydrogen can be separated from water by electrolysis, storing electric energy. It can then be used itself as a fuel in a stationary furnace or in a mobile heat engine (an automobile or an airplane, for instance). It could have an important role in all sorts of industrial processes, from metallurgy to coal gasification. Most important, used in connection with a fuel cell, it could produce electricity at the point of use more efficiently than we do now, and without the noxious pollutants (the residue of the fuel cell reaction between hydrogen and oxygen is water).

To obtain plentiful hydrogen requires more electricity. In our present framework, this means more coal or more uranium, and both these sources cause environmental problems. It may be that the true promise of hydrogen as a fuel is beyond the present framework, that its future lies with some of the new means of generating electricity that are the central topics of Chapter 7.

CHAPTER 7
Living on the Interest: The Continuous Energy Sources

Living on the Interest: The Continuous Energy Sources

There are many ways that we can stretch our fossil fuel supplies, and we have just described some of the technological assistance that is in the offing. There is also, as we described in Chapter 5, more fuel to be discovered and extracted if we give free rein to the "diggers and drillers" and support to extractive technology. This energy "capital," stored by the plants of long-ago earth, will probably last into the next century, but even if we follow this environmentally threatening policy, we will be simply postponing the inevitable. The supplies of fossil fuels are finite and they will run out. Set against our enormous and growing demand even the rich legacy of coal vanishes in a puff of smoke if we measure time in centuries rather than years. Spaceship earth carries fuel for only a limited voyage.

But Spaceship earth is not really on her own; she receives a vast and continuous supply of energy from her Mothership, the sun. As we saw in Table 2-1, the amount of power received from the sun per acre of this country's land area is 700 to 800 times as large as the average power we consume per acre. With the depletion of the fossil fuels, we are finally turning the inventiveness of our technology to the domestication of this source of power. We are, to use an imprecise metaphor, beginning the design of a future in which we live off the interest rather than the capital.

There are other continuous sources that we can tap, a few so large that we can consider them as almost continuous. Some of these are, in fact, "secondhand" solar sources. Hydropower, the power of falling water, we have already assessed. Wind is also a secondhand solar source. Its kinetic energy derives from the sun's heat which is absorbed in the earth's surface layer and sets into motion the complex currents of the atmosphere. We are renewing our interest in this source. We are also returning with new interest to the secondhand solar source in longest use, living material that stores the sun's energy by photosynthesis.

We will, in this chapter, look at the state of our technological mastery of these secondhand sources. We will also try to glimpse the future role of the non-solar source, geothermal energy, energy from the earth's molten core. We will not say more about tidal energy (it is too small for any important role in our future). Our best hope for the future, however, lies with the direct use of energy from the sun and in the development of fusion power, which could draw on the ocean's hydrogen for fuel. We will first look at the secondhand solar sources, as help is nearer realization in them.

The Secondhand Solar Sources

Wind, water, and wood, important sources of energy in this country at the end of the 19th century, have been displaced by the fossil fuels. They lost out because they were not properly packaged for man's use. Wind is erratic, waterpower is difficult to transport, and wood cannot supply enough energy per pound to allow it to compete with the fossil fuels. The final blow to the few windmills and waterwheels that lasted into the 20th century was struck by electricity. Relatively cheap, easily transported, convertible into almost any desirable form of energy, electricity, in addition, can be turned on and off at the flick of a switch.

The one secondhand source whose importance has survived and even grown is hydropower, for it was easily adapted to the generation of electricity. We have assessed its future in Chapter 2. Our technological advances allow us to look again at some of these secondhand sources, and it is the possibility of using them to generate electricity that receives our first priority.

Wind Power

Wind was harnessed by the primitive technology of earliest civilizations to move men and materials across the oceans. It has, since the time of the Romans, been used through the windmill for a variety of mechanical tasks—grinding grain, pumping water, etc.

The wind carries much energy. It is estimated that the power potential of the winds over the continental United States, across the Aleutian Islands and Alaska, and off the East Coast totals 100 billion (B) kilowatts, 200 times our present generating capacity. The estimate shown in Figure 2-1 is that the winds of the continental United States alone have about five times the total of our average power demand.

At the turn of the century this country made good use of wind energy. Our clipper ships were the most graceful and efficient sailing ships ever built and our western prairies were dotted with thousands of American-built windmills that pumped water and generated electricity. The clipper ships, however, eventually retired in the face of competition from the steady power of the steam ship and the dependability of its iron hull. The Western windmills lost the battle to inexpensive (subsidized, in fact) electricity from the REA (the Rural Electrification Administration).

But windpower may be coming back. A large electric generator, 1.25 Mw, was built in the 1940s in Grandpa's Knob in Vermont, but was shut down and never remodeled after a blade failure. The study of windmill turbines has been taken up again in New England, and William Heronemus, a professor of engineering at the University of Massachusetts, Amherst, has proposed an installation with aeroturbines of advanced design off the New England coast. He projects the possibility of generating 160 B kw-hr of electricity per year. (The New England region used 108 B kw-hr of electricity in 1970.)

A major drawback of wind power, as it is of solar power, is its variability. It is not possible to feed an electric system whose demand peaks and declines, as we show in Figure 6-4, with a source that cannot be predicted and controlled. It is here that some of the technology discussed in Chapter 6 will be called upon. A complete and dependable wind-powered electric generating system could store its energy as hydrogen, electrolysed from water by the generated electricity, and then provide electric power on demand by using fuel cells to regenerate electricity from that hydrogen.

There are many questions that must be answered, however, before the windmill returns to the American scene. One of the most important questions concerns weather modification that might be brought about by a battery of these devices removing a significant amount of the air's kinetic energy. Acquiring this knowledge, and the eventual harvest of some of this energy, wait on money. Such progress as has come so far has been from research supported at the hobby level. The projected 1975 Federal research and development budget, which was so generous to coal research (Table 6-2), contained only $7 million to be thrown to the winds. With $610 million in Federal research and development (R & D) funds spread over a 10-year period (less than the 1975 total research support for the breeder reactor), the prestigious NSF/NASA Solar Energy Panel (1972) projected that wind power could, by the year 2000, provide 19 percent of total electric power. Such R & D sums do not seem to be forthcoming, but even with the smaller support that will be available the windmill may make a comeback.

An even more exciting reversion to the past is signaled from Germany, where considerable effort has gone into the design of "Dyna-Ships," modern clipper ships with stainless steel sails and hydraulically turned masts. A full-scale, 17,000-ton Dyna-Ship, it is calculated, would consume (in its auxiliary engine) only 5 percent as much fuel as a similar size conventional ship. A Dyna-Ship is presently reported to be under construction, and if it fulfills its promise, the sail may return to the sea.

More Energy from Photosynthesis

We have always relied, through photosynthesis, on the secondhand energy of the sun for food, fuel, clothing, and building materials. As we saw in Table 2-1, this source is not impressive in its total. It is, nonetheless, ample enough to warrant consideration. Since much of the organic material (food, agricultural and wood processing wastes, newspaper and cardboard, for instance), are a solid waste problem in their own right, their conversion to energy would be doubly beneficial.

We will examine below several of the techniques for diverting more of the available photosynthetic energy into the nation's energy flow. These will include the production of liquid and gaseous fuels from organic material, their direct combustion to produce steam power, and some exotic techniques such as a plan to produce hydrogen directly by bacterial action on organic wastes and proposals to grow plants specifically for energy production.

Energy from waste: Each year we throw away millions of tons of combustible waste material. The disposal of this solid waste is itself creating serious environmental problems for us and it should, therefore, be easy to generate enthusiasm for projects to turn it to a useful end.

The total energy potential from organic solid waste is considerable, as is shown in Table 7-1. If converted to oil, for instance, the waste could provide 1.1 billion barrels (B bbls) per year, about 20 percent of our current oil consumption. However, as the table shows, much of this waste material occurs in small amounts at many sites and is not readily collectible. The estimated amount that occurs at large operations (big cattle feedlots, municipal collections, large sawmills, etc.) is, in fact, sufficient to produce 170 M bbls per year of oil, which is 12 percent of the amount of crude oil imported in 1971.

There are several pilot plants in operation to test the various methods to produce power and dispose of waste. In the pyrolysis process (burning in the absence of oxygen), developed by the Garrett Research and Development Company of LaVerne, California, organic waste is shredded, dried, and the inorganic materials (glass, metal, etc.) removed for recycling. The material is then reshredded and heated to 500°C in an oxygen-free atmosphere. Each ton of refuse produces 1 barrel of oil in addition to "char" and some low BTU gas (these latter by-products are burned to provide much of the heat for the process). Garrett has received a contract to build a 200-ton-per-day plant to handle all the solid waste from the California cities of Escondido and San Marcos. They will sell the fuel oil to the San Diego Gas and Electric Company at a projected operating cost of $8 per ton, less than the cost per ton of disposing of the refuse in that area. They estimate that a 2,000-ton-per-day plant could operate at a cost of $5 per ton and handle the output from a city of 500,000.

There are other less sophisticated experiments with burning waste for power. In one under way in St. Louis, about one-third of the daily garbage output is shredded and mixed with the coal burned in the power plants that serve the city. This useful end for garbage has been producing steam for European cities for many years and should grow in this country where land for landfills, the least costly means of disposal, is now scarce.

A more sophisticated method of converting organic waste to usable fuel is by hydrogenation, a process similar to the one used in the production of oil from coal.

TABLE 7-1

Amounts of Dry, Ash-free Organic Solid Wastes Produced in the U.S. in 1971 (in millions of tons)

Source	Wastes Generated	Readily Collectable
Manure	200	26.0
Urban Refuse	129	71.0
Logging and Wood Manufacturing Residues	55	5.0
Agricultural Crops and Food Wastes	390	22.6
Industrial Wastes	44	5.2
Municipal Sewage Solids	12	1.5
Miscellaneous	50	5.0
Total	**880**	**136.3**
Net Oil Potential (10^6 barrels, Mbbls)	1,098	170.0
Net Methane Potential (10^9 cubic ft., TCF)	8.8	1.36

Source: L. L. Anderson, Bureau of Mines, U.S. Department of the Interior.

In this process, waste is heated at high pressure and temperature in an atmosphere of carbon monoxide and steam. Some 99 percent of the carbon content can be converted to fuel oil, and even after recycling some of this oil (to provide for the steam), 1.25 barrels of oil per ton of dry waste are obtained. The sale of oil and the reduction in volume of waste to be disposed of make this operation competitive with other solid waste disposal methods.

In many ways the simplest way to obtain energy from organic waste is to produce methane from it. This, in fact, occurs naturally and many sewage disposal plants trap this gas and use it for heating. Methane is produced by anaerobic (oxygen-free) digestion of organic materials by micro-organisms. This "fermentation" process, it is estimated, could produce 10,000 cubic feet of methane or 25,000 Calories of energy from a ton of solid waste. The estimated potential of collectible waste (from Table 7-1) is 1.36 trillion cubic feet (TCF), 6 percent of the 1971 natural gas consumption.

An advantage of this system is that sewage already was a large component of the water that is needed as a growth medium for the bacteria. Methane as a fuel is, of course, very desirable and can be, by existing techniques, easily cleaned of potential pollutants. (Waste derived from fuels is generally low in sulfur.)

Energy farming: In this period of escalating fuel prices, it may even turn out to be commercially viable to grow plants specifically for their energy content. Although plants are not impressively efficient in their energy conversion processes (they average about 0.1 percent), there are some plants that can produce impressive amounts of organic material per acre. Table 7-2 provides some examples of the most productive species.

A proposal that has sporadically attracted interest recommends the conversion of appropriate crops to alcohol. There have been times, in recent history, when industrial alcohol (as well as some popular beverages) has been derived from cereals. In the war years (1940-1945), for instance, most industrial ethyl alcohol was made from molasses and other natural sources. When petroleum became cheap and plentiful again, alcohol derived from it completely took over the market.

TABLE 7-2
Annual per Acre Yields of "Energy Crops"

	Tons per Acre
Rubber (Hevea)	1
Sugar Cane	4 (sugar) 4 (pulp)
Sugar Beets	2 (sugar) 0.7 (pulp)

Source: M. Calvin, "Solar Energy by Photosynthesis," Science, 184, April, 1974, p. 375-381.

The rapid rise in the price of oil has brought fermentation produced alcohol back to a nearly price competitive position. Alcohol from sugar cane, for instance, can be produced for about 90 cents per gallon. Petroleum derived alcohol, although it is price controlled at 66 cents per gallon (and scarce), sells at $1 per gallon if bought outside the United States.

Sugar cane is an ideal crop for converting sunlight to sugar. It has the highest efficiency of solar energy conversion (0.6 percent) of any plant. It produces 4 tons of sugar (2 tons of alcohol or 625 gallons) per acre, and including the pulp, 8 tons of carbohydrate per acre. If, in Hawaii, for instance, one-third of the molasses production were converted to alcohol, it would make it unnecessary to import the 15 M gallons of gasoline the state uses to run its agricultural machinery. (Alcohol can be added to gasoline at up to 25 percent without any engine changes, and has the advantage of lowering the emission of pollutants.) There are other similar possibilities; the 7 M bushels of grain that spoil each year in Nebraska could produce 20 M gallons of alcohol.

The rubber plant is an interesting potential source of energy. It produces a pure hydrocarbon, not a carbohydrate containing oxygen that requires fermentation. It now yields about a ton of hydrocarbon per acre per year and the rubber growers predict that they could raise this yield to 3 tons. It is quite possible that this plant could take over much of the raw materials market (the equivalent of about 730 M bbls of oil per year, 6 percent of the total energy budget). It may well be that the rising price of oil will drive us back to the land for energy and that large "energy farms" will bring needed wealth to the tropical areas of the world.

Trees as fuel: A second way to bring more photosynthetic energy into the system is proposed by Dr. George Szego of InterTechnology Corporation. He has calculated that trees growing in sunny areas convert up to 3 percent of available solar radiation into energy in wood. The trees grown in an area of between 100 and 600 square miles of woodland could fuel (depending on the climate) a 1,000 Mw power plant over its 30-year lifetime. (Trees would be harvested in groups every 10 years.) Over the same 30-year period the plant would have used 74 M tons of coal, causing the strip mining of 40 square miles of land. The tree farm would have several advantages. The land could be used for recreation before and after logging, wood ashes are useful as fertilizer, and wood is low in sulfur content. Dr. Szego is convinced by his calculations that wood as fuel could be economically competitive with coal.

This scheme and many of the others ultimately suffer from the facts of life. The efficiency of photosynthesis is very small. It will probably be the case, therefore, that rather than cover land with these less efficient converters (even trees), these areas will be put to better use by covering them with, for instance, the more efficient "energy farm" of Meinels' vision we discuss in a following section.

The most practical proposals are those that entail the conversion of organic waste to energy, for we are already paying to dispose of that waste. Even here there is a hidden joker. These large amounts of waste are produced, in most cases, by inefficient practices elsewhere. We have so much waste paper because we don't recycle it, we have large amounts of cattle manure at feed lots because of the extremely inefficient practice of fattening cattle on grain to produce prime meat (meat marbled with fat). We will, in all likelihood, do better in the long run by replacing inefficient, waste-producing practices, rather than trying to extract some energy from the residue of these practices.

Geothermal Power

In Chapter 2 we took a brief look at the "energy stockpile" in geothermal form. Geothermal energy is presently in use in the generating plants of California's The Geysers field that provide about half of San Francisco's electricity. These plants use supersaturated "dry" steam, steam so hot that there is no water in it. This steam can be fed into conventional steam turbines.

There is much more energy available from the earth in forms other than dry steam, but its domestication will require a significant assist from technology. There is a potentially large reservoir of thermal energy in hot water or "wet" steam (steam at less than 350°) and in hot but dry rocks. The hot water wells could be tapped with a generator of the type we described as a "bottoming cycle" in Chapter 6, using as a working fluid a low boiling point liquid that could be vaporized and drive a turbine. The U.S.S.R. is reported to be using this technique with water at 108°F. A plant using isobutane has been designed for the United States, but money for pilot plant construction has not been forthcoming.

In addition to these low temperature cycles, other technological barriers awaiting penetration are: means of recharging hot, dry sources with new water, techniques of artificial stimulation (explosive fracturing for instance), and deep high-temperature drilling techniques.

Beyond pure electric power, the possibilities of geothermal energy broaden in a very interesting way. In many fortunately situated areas, Klamath Falls, Oregon, and Boise, Idaho, in this country and in many areas in the U.S.S.R., Hungary, Japan, Iceland, and New Zealand, the hot water is also used for home heating, industrial processes (a paper and pulp company in New Zealand), and even air-conditioning (working on the "adsorption-desorption" principle we describe in the following section).

In addition to heat, an important output from geothermal sources is water. The next big geothermal project in the United States is planned for the Imperial Valley. Under the Colorado River Basin Act, the Department of the Interior is to provide 2,500,000 acre-feet of water per year for the Colorado River. It is being proposed that a multipurpose geothermal development in the Imperial Valley could produce power, water, and minerals. To produce clean water, the hot brine would be pumped into a succession of "stills" at less than atmospheric pressure, the water would boil, the steam piped off, and the now-clean water allowed to liquify. The material that remains in the end is rich in many types of chemicals leached from the rocks and perhaps can be sold.

Withdrawing water at the rate being considered for the Imperial Valley brings on the danger of subsidence. It is proposed that water be reinjected — either irrigation runoff water or ocean water pumped inland. If this works, the Imperial Valley will, in fact, be a huge "geothermal desalination plant." Over a period of perhaps 100 years, hot water will be withdrawn, distilled with its own heat, replaced by salt water (or contaminated irrigation runoff), and this water will in turn be heated by the magma, drawn off, purified, etc. The projected cost is much less than any presently operating desalination plant.

Power from the Sun

As we saw in Table 2-1, all the secondhand sources of solar energy taken together do not form an impressive total of available power. With the continuing growth in demand, we are giving more and more serious attention to "mainlining" solar energy, converting it directly for our uses.

This search is not a new one; through the ages man has been impressed by the power of the sun and even occasionally turned it to his uses. Archimedes, according to the legend, used focusing mirrors to set fire to invading Persian ships, and small, solar-heated steam engines had some success a century ago. But techniques to use solar energy as a reliable and large-scale source of power have not been developed, for obvious reasons. Solar energy is dilute, so that a large capacity requires a large collection area. To obtain 1,000 Mw of power, for instance, requires, according to Table 2-1, about 1,250 acres or about 2 square miles of surface area at 100 percent collection efficiency. At lower collection efficiencies, the areas are correspondingly larger — 20 square miles at 10 percent efficiency.

It is also an erratic rather than a reliable source, fluctuating on the predictable day-night cycle and unpredictably with the cloud cover. We are, therefore, faced not only with the need for a large collection area, but also with the problem of storing the energy once it is collected.

These handicaps have served so far to keep experimentation with this energy at the hobby level. Our newly realized energy shortage has, however, caused a new flow of federal research support into solar energy research, and several methods for domesticating the sun are now being actively investigated. Work is proceeding along three different lines; solar home heating and cooling, solar cells for direct conversion to electricity, and large central solar power plants for the production of electricity.

Solar Homes

The most simple energy conversion for the incoming solar radiation is into heat energy.

There is much to recommend emphasis on direct use of solar energy in the home. There is a large potential market; some 20 percent of the total energy bill goes into heating and cooling residential and commercial buildings, and, further, the conversion to heat energy is a highly efficient one. It follows the arrow of the second law. Collectors capable of converting as much as 80 percent of the incident radiation to heat have been demonstrated.

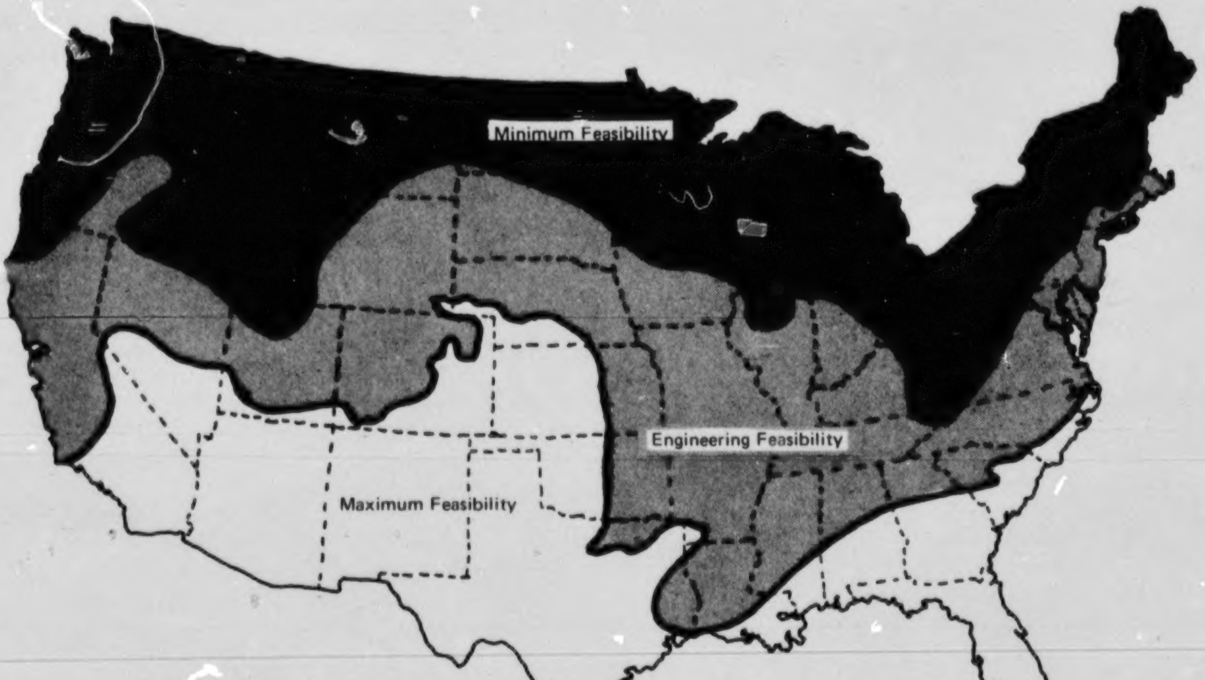
The techniques of heating and cooling with solar energy are quite simple. A dwelling's roof provides ample collection area. The solar incidence of Table 2-1 is equivalent to 350 Calories per square foot per day. A typical residence for a family of four with 1,600 square feet of roof area will receive, on the average, 2,000 M Calories of solar energy in a year, some six times the average 32.5 M Calories required for space heating. These averages, of course, do not display the difficulties — the major fraction of this energy arrives during the summer months, when heat is not needed. Even with this disclaimer in mind, however, there are large areas of the United States that do receive enough steady solar power to take care of their total need for space and water heating. These areas are shown as the zone of "maximum feasibility" in Figure 7-1. The second zone, roughly covering the middle latitudes of the United States, is one of "engineering feasibility"; some auxiliary heating would have to be provided. For the zone of "minimum feasibility," solar heat would be the auxiliary heat source, supplementing conventional systems in the spring and fall.

Heating is accomplished by "flat plate collectors," essentially blackened plates covered by one or several transparent insulating layers. The transparent layers prevent cooling of the blackened absorbant plate by air currents. They can be made selectively transparent, admitting the incident short wavelength radiation, but reflecting back to the absorbing plate the longer wavelength infrared "heat radiation." Water pipes are then put in thermal contact with the back of the plate and carry the heat energy into some kind of a storage reservoir. The complete solar home might look like that in Figure 7-2.

Several storage techniques have been tested; hot water storage is sufficient for a few days as are heated rocks or pebbles. More sophisticated techniques now being developed use salts that are melted (absorbing

FIGURE 7-1

Solar Home Heating Feasibility



The regions of the different degrees of feasibility of heating houses by solar energy. In the white areas houses may be entirely heated in this fashion; in the light-gray areas a large portion of the heat can be obtained; and in the darker areas only a small part of space-heating needs can be provided by trapped solar energy.

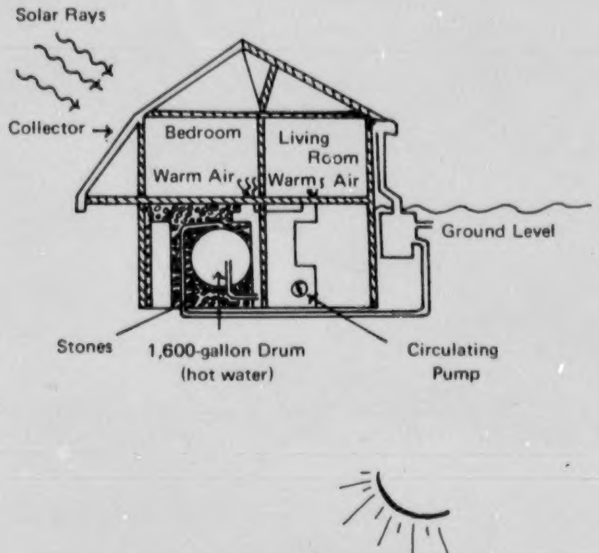
Source: **Energy Sources, the Wealth of the World.** Ayres and Scarlott, (New York: McGraw-Hill) 1952.

energy) during the collection period and then solidify, releasing energy when it is needed.

Such a system could carry the heating load by itself in the maximum feasibility zone shown in Figure 7-1. In the zone of engineering feasibility, a back-up heating system would be needed for a succession of cold cloudy days. If these two systems are combined, if an electrical back-up system is provided, for instance, the storage system can be recharged when necessary by electric heaters during the night time, using low-cost off-peak power.

The technology to accomplish what has been described already exists. In fact, solar heated houses have been operating in various parts of this country for many years — one in Boston has consistently supplied about half of its own total heat needs for 20 years. They have already demonstrated cost competitiveness. Table 7-3 shows the results of the most recent analysis of the relevant data and compares the cost of solar heat (dollars per M Calories) with electric, gas, and oil heating. In this analysis, the comparison takes into account fuel costs as well as capital requirements and operating costs, and assumes a 20-year life cycle for the building.

FIGURE 7-2
Home Solar Heating System



Solar Collector

It is clear, even from this data, that solar space and water heating is the most economical one in some parts of the country (it appears to be competitive with gas and oil in Santa Monica, California). In most parts of the country, it is more economical than electric heating. In light of this knowledge, one wonders why electric home heating has been enjoying the boom we described in Chapter 4 (a 470 percent increase from 1960 to 1968), while solar heating is still a novelty.

The answer to that question underlines the real barriers to wide utilization of solar heat. These barriers are not technological but economic and practical. The dominant consideration in the purchase of a home seems to be the purchase price — the capital investment. Solar heating is add-on heating, since it at least has to be backed up by a conventional heating capability. Even in the zone where solar heating alone is enough, the initial cost of the solar equipment is larger than the cost of conventional facilities. Solar heating systems are capital intensive. This means that the mortgage company gets into the act, that the house may be harder to sell, etc. Electric heating, on the other hand, is initially economical; it requires no complex equipment, no furnace ducts or pumps. Also, it is convenient to operate and maintain, another primary consideration to the purchaser. With the present mobility of Americans, we are not accustomed to considering 20 or even 10-year life cycles of houses, and this set of mind is present not only in buyers, but in builders, insurers, and all the others involved in the housing business. But it is only on such a basis that the savings from free fuel will become impressive.

These savings are now more impressive than are shown in Table 7-3. Even in the instant since 1970, the overall energy picture has changed drastically, greatly enhancing the competitive position of solar energy. The $1.85 per million BTU[1] for natural gas that Table 7-3 shows for Massachusetts is now $2.00. Other fuels, even electric energy, are rising in similar fashion. The clear message of all our energy studies is that this increase will continue. It would seem that new efforts to stimulate mass production of solar heating units, and to change building codes, insurance and mortgage regulations etc., can now be justified on an economic as well as an energy ethic.

Additional economies accrue if solar energy is used to provide cooling as well as heating. The inherent advantage of solar cooling is the obvious one: cooling is most needed at the time when the maximum amount of solar energy is available. Since a fairly large solar collector is needed (1,000 square feet for an ordinary house), the solar collector itself, if mounted on the house roof, provides insulation that reduces cooling need. This large collector system is also more than sufficient for the winter heating requirements.

In the process of solar cooling the energy required to compress and circulate the refrigerant fluid is provided by heat instead of by electric pumps. One prototype design uses ammonia which is evaporated by heat absorbed in the area to be cooled. Ammonia is chosen because its boiling point is −40°C, well below the inside temperature of a refrigerator. The ammonia vapor carrying the heat is then absorbed in a water-salt solution and circulated (by convection currents caused by the temperature difference) in tubing outside of the refrigerator or house, where the heat is released to the surroundings. The solar energy source then is used to drive the ammonia vapor out of the water-salt solution and regenerate the ammonia liquid.

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[1] A BTU is equivalent to about 0.25 Calories.

Even simpler solar cooling is used in several solar houses by reversing the solar heating cycle. Water from the storage tank is circulated through the roof-top collector at night radiating heat into the night sky. The now-cool water is stored and used to cool the house in the daytime.

All in all, expert opinion is that the technology for solar cooling, as well as for solar heating, is ready for large-scale application. Given the ready status of technology in the heating/cooling front and the lack of action to date, it is encouraging to see even small movements in the right direction. There has been increased support from Congress, where there has been discussion of legislation to provide for the construction of 5,000 or so demonstration solar homes. This project, if carried out, should lead to the needed breakthroughs in architecture, building, regulation, finance and other related areas. There appears, at last, to be the beginning of serious commercial plans to produce solar equipment. Within five years, we may be able to judge what portion of the home comfort energy can be taken from the sun.

Solar Cells

The most glamorous conversion techniques use solar cells to convert radiant energy directly into electric energy. The energy conversion is accomplished by the photovoltaic process; on striking certain materials solar radiation is absorbed and causes a separation of the electrons from the atoms. The migration of these electrons in one direction and the positively charged ions in the other produces a small potential difference, typically about 0.5 volts. An array of these cells can produce a useful electric power capacity.

The present handicaps are many: solar cells must be made from very high purity materials; single crystals of silicon are preferred. While silicon is the most abundant material in the earth's crust, it is not easily refined and shaped for use in solar cells. With present technology the cells are produced virtually one by one, in what is essentially a "cottage industry." They cannot yet be mass produced. Although efficiencies of conversion have increased from 9 percent in 1965 to 11 percent in 1971, and energy conversion costs in dollars per watt have decreased by nearly a factor of 10, the cost of the energy they produce is still beyond any reasonable competitive range. The present costs of the best solar cells for spacecraft use are $300 to $1,300 per watt (this must be compared with $250-300 per kilowatt in fossil fuel and nuclear reactors) and 3,000 to 13,000 mills* per kw-hr (compared to 6-8 mills per kw-hr from conventional sources). It is clear that reductions of several hundred-fold in solar cell cost will be needed to allow their serious consideration for any use other than in space or very remote terrestrial locations.

There are many who believe these cost reductions can be achieved, and advance planning for their use continues. One of two very different but illustrative proposals calls for their incorporation into the roof of a residence — now being implemented at the University of Delaware. The other would put a large array of solar

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*A mill is 0.1 cent, or $0.001.

TABLE 7-3

Costs of Space Heating (1970 Prices in dollars per million BTU[a] useful delivery)**

Location	Optimized Solar Heating Cost in 25,000 BTU/Degree-day House, Capital Charges @6%, 20 years		Electric Heating, usage 30,000 kw-hr per year[b]	Fuel Heating, Fuel Cost Only	
	Collector @ $2/ft.	Collector @ $4 per ft.		Gas	Oil
Santa Maria	1.10	1.59	4.28	1.52	1.91
Albuquerque	1.60	2.32	4.63	0.95	2.44
Phoenix	2.05	3.09	5.07	0.65	1.89
Omaha	2.45	2.98	3.25	1.12	1.56
Boston	2.50	3.02	5.25	1.85	2.03
Charleston	2.55	3.56	4.22	1.03	1.83
Seattle-Takoma	2.60	3.82	2.29	1.96	2.36
Miami	4.05	4.64	4.97	3.01	2.04

Source: R.A. Tybout, and G.O.G. Lof, "Solar House Heating," **Natural Resources Journal** 10 (2), April 1970, pp. 268-326. pp. 268-326.

[a] Heating values are usually given in BTUs. For comparison with other Source Book data remember that 1 Calorie = 4 BTU.

[b] kw-hr = kilowatt-hours.

cells into a synchronous orbit to collect and convert solar energy and beam it back to earth by microwave.

There are several interesting features of the Delaware house. The roof is covered with transparent panels that shield the solar cell collectors. The panels also collect heat, which is stored in a "frozen salt" reservoir of the type we have described. A "heat pump" (see Chapter 3) transfers heat from the reservoir to the house, or pumps heat from the house to cool it. This combination increases the overall efficiency to perhaps 60 percent. The solar generators are to be connected to utility lines in a two-way arrangement. When they are generating more power than the house needs, it is sent through the utility lines and credit is received. When the solar cells cannot produce enough power, the flow is reversed. Since the solar cells generate maximum power during the afternoon peak-load period, the system works to the utility company's advantage in most instances. The test of this interconnected system will be watched with interest.

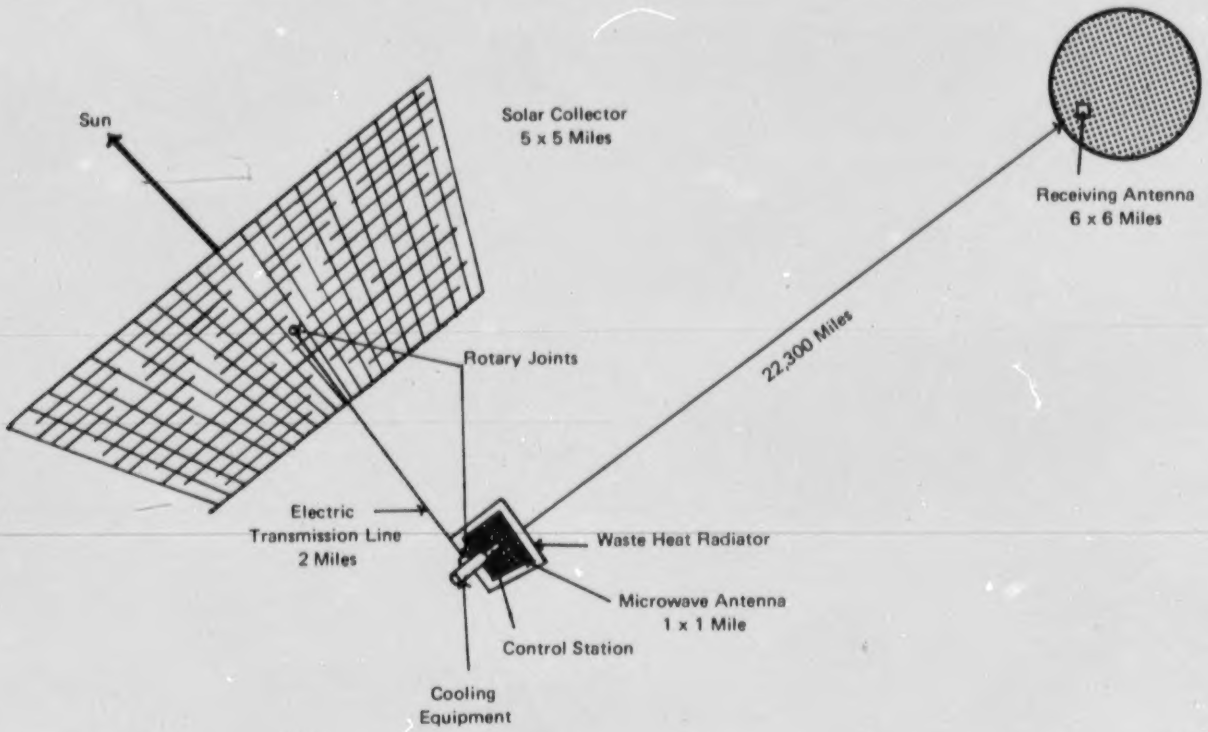
Central Power Stations

At the other extreme is the proposal by Peter Glaser, of Arthur D. Little, Inc., to put a large array of solar cells into a synchronous orbit about the earth and beam the collected energy back as microwave radiation. A sketch of the proposed arrangement is shown in Figure 7-3. The advantages of the satellite solar array come from its nearly constant exposure to full sunlight. By intercepting the sunlight before it is reflected by the atmosphere, by removing the day-night cycle and avoiding clouds, it could be expected to receive at least six and maybe as much as 15 times more energy per square feet than a ground location.

Even with this higher level of input power, the size of the array, if it is to generate a significant amount of power, is impressive. A 10,000 Mw generator would need 25 square miles of solar cells, and these arrays would have to be steered to face the sun. The microwave antenna that beams the power to earth would be a mile on a side, and the receiving microwave array on earth would be six miles on a side.

It is clear that the expensive solar cells used in spacecraft presently, that cost $3,000-$13,000 per square foot, cannot be used in such an array; 25 square miles of these solar cells would cost $2 trillion, twice the United States GNP. If the cost can be lowered by a factor of 100 or so by technological breakthroughs and mass production efficiencies, the beaming and receiving of such large amounts of power can be accomplished efficiently, and with transportation provided at reasonable cost, these satellite stations might become feasible. They are now some decades, at least, in our future.

FIGURE 7-3
Proposed Satellite Power Station



Source: Peter E. Glaser, Arthur D. Little, Inc.

There is a reasonable hope that less expensive solar cells can be built from materials other than silicon. Cells built with cadmium show promise. (Cadmium sulfide cells are used in the Delaware solar house.) Dr. K.W. Böer, of the University of Delaware, believes that the cost of these cells, if made by mass production techniques, could be brought below $5,000 per kilowatt.

While we await further reduction in the price of solar cells, we can experiment with another method of obtaining electricity from sunlight.

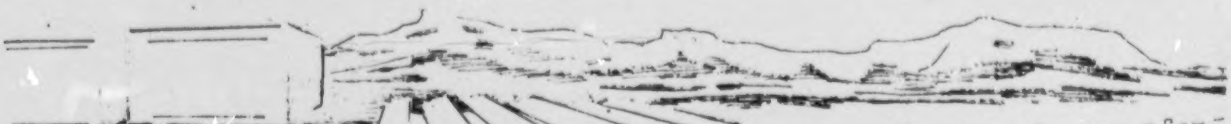
Solar Energy Farms: While the use of large arrays of solar cells to convert solar energy to electricity does not appear economically feasible for a decade or so, there is growing interest in a simpler thermal collector system that may reach the pilot model stage within the next decade. The strongest advocates of this plan are a husband and wife team, the Meinels of the University of Arizona. They propose to trap and focus solar radiation by rows of transparent collectors, pump the heat to a central plant, generate steam, and produce electricity in the conventional manner. An artist's conception of the collector array on a "solar farm" is shown in Figure 7-4. Sodium, a proposed heat transfer material, would be liquified by the heat, and conceivably temperatures could reach as high as 1,000°F.

The heart of the system is the collector shown in Figure 7-4. The liquid sodium, which will carry the heat energy to the generating plant, is enclosed in a pipe that has a very efficient absorbent coating on it. To increase the amount of energy collected, there is a curved mirror under the pipe that focuses sunlight on the pipe. All this is enclosed in a vacuum to reduce heat leakage.

The rest of the system is fairly standard. The heated material in the pipe flows to a storage tank (which has enough capacity to last through a couple of cloudy days) and then generates steam for the turbine. The overall system efficiency expected by the Meinels for their "Early" system is 14 percent and for the "Mature" system, 28 percent. The near 30 percent efficiency of the "Mature" system compares very favorably with conventional electric generating efficiency.

To produce half the 10 B Mw-hr (which is the high projection of Chapter 4 for the consumption of electric energy in the year 2000), 10,000 square miles of land will be needed. That is a parcel of land 100 miles on a side. This is a lot of land, but distributed through the six to eight "sunshine states" the total impact would not be overwhelming. The Meinels call their system a solar farm to emphasize the comparison between setting land aside to convert solar energy to food energy, and their planned conversion to electricity. Since some 500,000 square miles of land are now set aside to grow food (at less than 1 percent efficiency), which only provides 1 percent of our total energy consumption, the comparison makes its point.

FIGURE 7-4
Solar Farm



Source: "Solar Energy," Arthur R. Tamplin, **Environment**, **15**, #5, June 1973.

As we have said, solar energy enjoys a big advantage over most other forms. It can be used without unbalancing natural cycles. The solar farm makes the point beautifully. Under normal circumstances, the desert absorbs about 65 percent of the incident sunlight and reflects the remaining 35 percent. With the collectors in place, 95 percent of the incident radiation is absorbed, but 30 percent of this (the generated electricity) is transmitted to other areas, and the remaining 65 percent is returned as leftover heat. Thus the local balance remains the same. We should also point out that the same potential uses of leftover heat exist for the solar plant as for any other thermal plant — desalination of water is one suggested use.

The Meinels have received some National Science Foundation research support to study the technical problems associated with such preliminary matters as the absorbing coatings. They are hopeful of forming a large group to begin planning and constructing a prototype plant that will show that their estimate of 5 to 6 M kw-hr electricity is within the range of possibility by the mid-1980s. They may well have started us on the way to much more efficient farming of the sun's free energy.

The Sea as Solar Collector

The problem in utilizing solar energy on a large scale is that massive collection areas are needed. A crowded world may not be able to spare enough land area for such use. It is natural, therefore, to turn toward seas, whose surfaces we put to minimal use.

Since the seas are warmed from the top rather than from the bottom, they do not have the strong vertical mixing currents characteristic of the atmosphere. Their "winds" are the gentle currents like the Gulf Stream. As a result there are significant temperature differences between the surface and the deeper layers. In tropical regions this difference may be as high as 20°C (36°F) between surface and 1,000-foot level. It is possible to conceive of a heat engine operating on this difference.

In order to operate at such a low temperature, a solar sea plant would have to employ some low boiling point liquid, such as ammonia, as the working fluid. The small temperature difference would, of course, set a small upper limit, perhaps 5 percent, on the thermal efficiency (since T_{in} is almost equal to T_{out} in the efficiency equation), and practical efficiencies of 2 to 3 percent are all that can be actually expected.

The operation of the power plant is similar to the steam plant. Cool ammonia liquid at relatively high pressure is pumped to the surface region and is warmed by surface water flowing through a heat exchanger, becoming a high-pressure vapor that can turn a turbine. The vapor, now at a somewhat cooler temperature, is pumped back down to the condenser, where the cooler water condenses it to the liquid state.

The solar sea power plant has several theoretical advantages. Neither high temperatures nor pressures are encountered. In fact, the hydrostatic pressure of the sea water could be used to balance the pressure in the boiler and condenser. The resulting system could conceivably have routine maintenance performed while it is running.

The problem of energy storage or transmission could be solved, it is suggested, by using the electricity to electrolyse water with the resulting hydrogen and oxygen shipped or piped to shore. By conducting the electrolysis at great depths, the gases could be produced and stored under pressure, thus eliminating the cost of compressors.

The largest advantage is, of course, the enormity of the energy reservoir. It is estimated that the Gulf Stream, which brushes the Florida coast, could provide 182 B kw-hr of electric energy — 75 times the expected United States demand by 1980. A group at the University of Massachusetts is presently preparing and seeking preliminary support for a 400 Mw solar plant to be located about 15 miles offshore from Miami.

Solar sea plants could provide other useful products in addition to power. Sea life might blossom in the nutrient-rich cold water pumped to the surface. Environmental effects seem to be potentially benign also. Since the heat transferred from the warm surface to the deeper layers will be replaced by more solar absorption at the surface, the net effect would be a slight overall warming.

In spite of the size of the resource, and the optimistic predictions of cost ($165 per kw or 3 mills per kw-hr), there has been no appreciable funding of research in this area. It may well be that the first step will be to develop the techniques of low-temperature turbines, which are crucial to the success of these plants. Such turbines are also useful as "bottoming cycles" on conventional plants and in the development of the lower temperature geothermal sources. The proposals for solar sea power currently in the literature may be, as was the similar proposal by the French physicist, D'Arsonval, in 1881, "before their time." The large thermal reservoir of the ocean, however, will continue to attract the attention of energy seekers.

Fusion—The Big If

The confluence of increasing demand and finite resources that we have pictured leaves us with uncertain prospects of an energetic future — only the breeder reactors give promise of fuel for as long as thousands of years. We have seen in this chapter that there are some promising technologies that may, sometime within the next 5 to 30 years, enable us to stretch the fossil fuel supplies and even tap into some of the energy that is continuously supplied to earth. Solar energy is the big "if" of the continuous sources. There is an equally big "if" among the depletable sources that we have not yet discussed — the fusion reaction that would tap the nuclear energy of light nuclei. An understanding of the source of this energy begins with the plot of "binding energy per nucleon" vs "mass number" of Technical Appendix 6. As we point out in that discussion energy is released when two light nuclei combine — fuse — to form a heavier one. The most productive nuclear reactions of this type are expected to be reactions involving the "isotopes" of hydrogen — deuterium (H^2), which has a neutron as well as a proton in its nucleus, and a radioactive form of hydrogen called tritium (H^3), which has two neutrons and a proton. There are several nuclear reactions (rearrangements of the particles within the nucleus) involving these hydrogen nuclei that release significant amounts of energy.

The fusion reaction has several advantages as an energy-producing reaction. First, the radioactivity release is much less serious than it is in fission; only tritium among all the participating nuclei is radioactive. Second, the fuels (isotopes of hydrogen) are very plentiful, since hydrogen is the most abundant element. Even though deuterium is a rare form of hydrogen (only one out of each 6,000 hydrogen atoms will be in the form of H^2), the sea is a potentially huge source. If we can make these nuclear reactions work, then one cubic kilometer of sea water has energy content greater than all the fossil fuels on earth. Said in another way, the deuterium content of the oceans (only 1/6,000 of their water) can provide the energy equivalent that the oceans would provide if they were filled with gasoline — and 300 times as large. Here is energy potential stretching into our distant future. That's the good news.

The bad news is that we have not mastered this reaction in spite of $400 million in research funds spent during the past 25 years in the United States and $1 billion in the world. The problem is not in obtaining pure deuterium; it is relatively easy to separate H^2 from H^1 since one is twice as heavy as the other. The problem is in bringing deuterium nuclei together closely enough to make them stick; that is, closely enough to let the very short-range nuclear forces take over. Since the nuclei are electrically charged, they normally repel each other. To force them together takes energy; they have to climb an electric hill, so to speak. The only practical way to give a large number of nuclei such energies is to heat them. But there is the catch; in order to assure that a sufficient number of nuclei have enough energy to cause fusion, the sample of deuterium must be at a temperature of at least 50 million° C, hotter than the temperature at the center of the sun. The only successful heating to that scale that we have so far achieved was by exploding the A-bomb and in this way triggering the fusion reaction of the H-bomb. This method in large-scale use would provide a solution of sorts to our energy crisis — but not a very humane one.

The scope of the problem becomes clearer. To achieve fusion, solid deuterium or deuterium gas at an appreciable density must be held in a container and heated to temperatures at which any container will vaporize. Thus, means must be found to achieve this heating of deuterium, and yet keep it out of thermal contact with its container. There are two ways that this problem is being approached, by magnetic confinement and by laser bombardment.

There are several approaches using magnetic confinement undergoing active experimentation. In these processes the deuterium gas is decomposed into a "gas" of charged particles, a "plasma." The energy to accomplish this is provided in several ways, usually by causing a large electric current to flow through the gas. Charged particles can be controlled by magnetic fields. Several different magnetic field shapes are being tried, a doughnut shape (the torus), a straight pipe with magnetic fields that turn the particles around at the ends (the "magnetic mirror"), and a pulsed field that tries to bring everything together at once with a single large burst of magnetic fields (the "theta pinch").

There are three parameters which must be controlled to make fusion work: the temperature, the density, and the confinement time. The deuterium has to be hot enough, dense enough, and hang together long enough, to produce a self-sustaining fusion reaction. A crude measure of feasibility is provided by the so-called "Lawson criterion," which predicts that for a deuterium-tritium fuel mixture heated above the ignition temperature (50 million°C), the product of the density and pressure must be at least 10^{14} seconds- fuel ions per cubic centimeter. Breaking this down, the rough criteria are that densities of 10^{14} - 10^{15} fuel ions (corresponding to pressures of one ten-thousandth or one hundred-thousandth of atmospheric pressure) *must be* held together for 0.1 - 1 second. While each of the three target values of temperature, density, and confinement time has been separately reached, no single experiment has yet been able to put them all together. The closest contender so far is one of the "doughnut" machines, the ST Tokomak, an American adaptation of a Russian device. This machine has achieved a time-density product of 3 to 6×10^{11} (but at a temperature well below ignition). It is expected, however, that the Tokomak principle will produce a successful controlled fusion reaction when larger machines are tested in the late 1980s.

Achievement of the necessary temperatures, densities, and pressures will demonstrate scientific feasibility; beyond that is the murky uncertainty of engineering feasibility. But before we explore that region, we must mention the second approach to fusion, laser bombardment.

Laser Fusion

In this approach, the problems of density and confinement time are to be circumvented by bombarding a small pellet (about one millimeter in diameter) of frozen deuterium-tritium (frozen at 20° above absolute zero) with an energetic laser beam. The pulse of energy from the laser is to be poured into the pellet so quickly that its inertia holds it together while it heats to fusion ignition temperatures.

The laser fusion arrangement is shown schematically in Figure 7-5. The target pellets drop one by one into a chamber and are struck by a focused pulse of laser energy. Each pellet heats rapidly, fusion occurs, and the pellet explodes with the force of 500 pounds of TNT. The amount of laser energy needed and the problems of holding the pellet together are minimized if laser beams are broken up by a series of mirrors and focused on the pellet from all sides. This technique produces an "implosion," greatly increasing the pressures and temperatures in the interior of the pellet.

The explosion products fly out until they strike the walls of the chamber, where their kinetic energy is converted to thermal energy that can be used to generate steam. The implementation of this process faces several difficulties. The construction of a chamber that can hold up under steady explosions is one of them. Laser power is a second requirement. We have no lasers capable of the necessary power at present. A further problem is the cost of the pellet. Since each explosion will release energy, which when converted to electricity is only worth about 1 cent, extremely inexpensive means of pellet fabrication must be found.

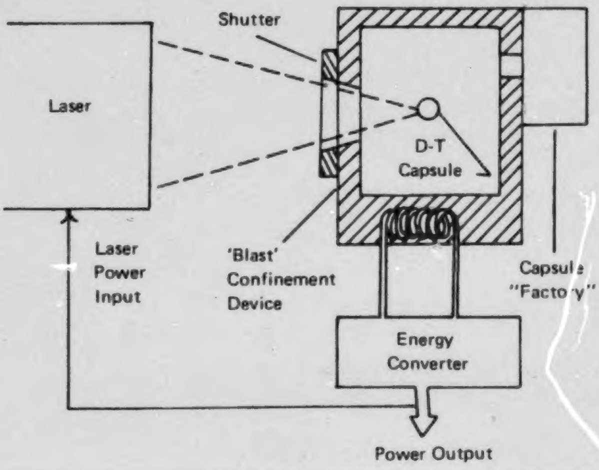
Laser fusion, in its infancy, has generated much enthusiasm and greatly increased research support. Its proponents see it as providing power sources of conveniently small size — 50-100 Mw of electric generating capacity — allowing dispersion to industry, use in ship propulsion, and providing on-site power for urban areas. Its detractors don't believe it can be made to work. The answers may come first from the U.S.S.R., where a new, more powerful laser may be the first to cause this type of fusion to occur.

Fusion Power Plants

It is conceivable that scientific feasibility of the fusion reactor may be demonstrated in the 1980s. The problems, however, will be only beginning. While the fusion process does not have the huge radioactive inventory of fission to deal with, it has a new problem, high-energy neutrons. The large fluxes of these neutrons will cause structural damage, the seriousness of which is difficult to estimate. It is feared, however, that it may be impossible to find materials that will stand up under them long enough to make commercial operation practical.

FIGURE 7-5

Laser-Fusion Power Generator



Source: Briefings, Task Force on Energy, Subcommittee on Science, Research and Development, Committee on Science and Astronautics, U.S. House of Representatives, Serial M, 1971 p. 47.

The large magnetic fields required will also be a problem; they will probably have to be provided by superconducting magnets operating at near liquid helium temperatures. Thus the reactor will be 100 M degrees at its center and a few meters away will need to be near absolute zero. The magnets will also have to be shielded from neutrons.

As we have earlier suggested, the only fusion reaction in use for a considerable time will probably be the one using tritium. This also poses problems. Tritium will, no doubt, be bred from lithium by fast neutrons. The reacting chamber will probably be surrounded by lithium, liquified by the heat. The tritium created by neutron bombardment is pumped from the lithium to be used as a fuel, and the hot lithium creates the steam for a generator.

There are some drawbacks to reliance on the $H^2 + H^3$ reaction that requires lithium for the production of H^3. Lithium is not a plentiful material; proved lithium resources (reserves) would only provide energy equal to that available from all the fossil fuels. There has, however, been no intensive search for lithium, and the available resources are probably great enough to power us for at least thousands of years.

Fusion reactors might be used to increase our energy supplies in a different way. The existence of the large flux of high-energy neutrons might eventually make it possible for the "breeder reactions" using U^{238} and Th^{232}, which we have mentioned, to take place, and thus allow the fusion reactors to supersede the controversial breeder reactors as a source of fissile materials for light water reactors.

Because of the high temperature of the steam produced, the fusion reactor could be very efficient, 50-60 percent. Since in the $H^2 + H^3$ reaction the products are charged particles, it may also be possible to separate them in a weak magnetic field that covers a large area in a fashion similar to that used in the magnetohydrodynamic generator (MHD). This direct conversion of kinetic energy to electric energy would be even more efficient, perhaps approaching 80 percent.

When?

Within three years after the discovery that U^{235} could produce a chain reaction, Fermi and his colleagues had demonstrated one in a pile of graphite blocks under the University of Chicago's football field, Stagg Stadium. It has now been more than 20 years that the physics of fusion has been well understood, but its "Stagg Stadium" has not yet occurred. For this reason, prophecy is dubious. It does appear, however, that the increase in research support that the energy crisis has stimulated will allow the construction of bigger machines, and that from one or more of them we will obtain evidence of scientific feasibility sometime before the mid-1980s. As we have said, however, achieving scientific feasibility is the equivalent of getting our heads above water, the long swim to shore is still ahead.

We are accustomed in this explosive century to seeing all dreams come true. Any idea that is conceivable can eventually, through genius and the magic of money, be implemented. One has to be reminded from time to time that the inevitability of progress from conception to commercial realization is a belief, not a law of nature. The engineering difficulties, on whose solution the commercial future of fusion waits, are enormous. The optimists confidently predict pilot plants by 1990, the pessimists warn us that this future may never come.

Summary

In this chapter we have examined some of the potential energy sources that may make energy again abundant. There are only two sources of a size not dwarfed by our rapidly expanding consumption, solar energy and energy from the fusion of hydrogen isotopes.

Solar energy is, of course, the major source of earth's energy, at present providing food and fuel, and the secondary sources of water and wind power. The size of this source and its daily delivery are causing us to turn more directly to it. There are no technological barriers to the immediate employment of solar energy for home heating and cooling, and the new energy situation should cause rapid advances in that area. Large-scale conversion of solar energy to electric energy waits on the development of more economical solar cells and on the mastering of the complexity of large-scale collection and thermal conversion.

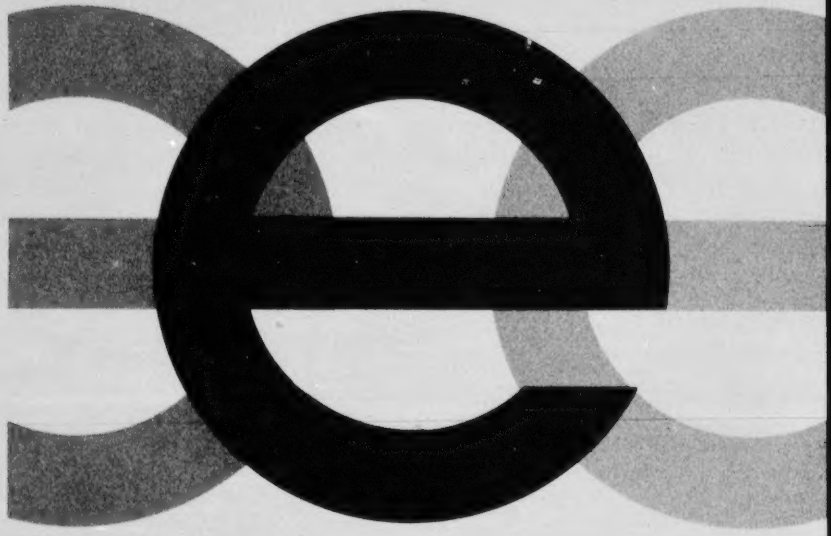
There are other continuous sources that are beginning to attract attention and of these, geothermal energy and improved use of photosynthetic energy show the most promise. Both of these are potentially benign environmentally and some of the proposals for improved photosynthesis, those which use organic waste as fuel, hold out the promise of mitigating other environmental problems as well.

Some of the other continuous sources could make large contributions. However, at present there is little evidence of concrete interest in wind power or in solar sea power, which need exotic technology to realize their potential.

The other "Big If" is fusion power, which could draw its fuel from the sea and cater to our needs for hundreds of thousands of years. The difficulties of this "If" are technological: it has not yet been possible to hold enough deuterium together long enough and get it hot enough. The optimists look to the demonstration of scientific feasibility by the mid-1980s, but it is clear that even in such an optimistic view, fusion reactors will not make much of a contribution to our 20th-century needs.

The visions that are put forward in Chapter 7 have, perhaps, lifted some of the gloom that has been growing throughout the book. There is hope for the future. None of these techniques or sources offers immediate relief to our present desperate state, but they do give us incentive to attack the problems of the present with determination and optimism.

ENERGY-ENVIRONMENT SOURCE BOOK



Technical Appendices

APPENDIX 1
Glossary

Glossary

absolute zero — The temperature at which, according to the general gas laws, a gas would exhibit no pressure. If substances were to behave as gases at all temperatures, the temperature at which random molecular energy is zero. It is equal to −273.16° Centigrade or −459.7° Fahrenheit.

alpha particle — The positively charged nucleus of a helium atom. A nuclear cluster consisting of two neutrons and two protons which is one of three types of emissions by naturally radioactive elements. It can also be produced through nuclear reactions.

ampere — A unit of measure for electric current. The charge flow per unit time. It is equivalent to a flow of approximately 6×10^{18} electrons per second.

annual rate of growth — The percentage by which a quantity increases each year.

base load — The minimum load of a utility (electric or gas) over a given period of time.

barrel (bbl) — A liquid measure of oil, usually crude oil, equal to 42 gallons or about 306 pounds.

bituminous coal — Soft coal; coal that is high in carbonaceous and volatile matter.

black lung — A respiratory ailment, similar to emphysema, which is caused by inhalation of coal dust. Identified as a contributing cause in the deaths of many underground coal miners.

bottoming cycle — A means of using the low-temperature heat energy exhausted from a heat engine, a steam turbine, for instance. It usually employs a low-boiling point-liquid as working fluid.

breeder reactor — A nuclear reactor so designed that it produces more fuel than it uses. Uranium 238 or thorium 232 can be converted to the fissile fuel, plutonium 239 or uranium 233, by the neutrons produced within the reactor core.

British Thermal Unit (BTU) — A unit of heat energy equal to the quantity of heat necessary to raise the temperature of one pound of water one degree Fahrenheit. It is equal to one-quarter of a Calorie.

brownout — The deliberate lowering of voltage (and, thus, the power supplied to all users) by electric utility companies, employed when demand for power exceeds generating capacity.

Calorie — A unit of heat energy equal to the amount of heat that will raise the temperature of one kilogram of water 1° Centigrade. It is approximately equal to 4 BTUs. (In scientific terminology this is the kilocalorie, 1,000 small calories.)

carbon dioxide (CO_2) — A compound of carbon and oxygen formed whenever carbon is burned.

carbon monoxide (CO) — A compound of carbon and oxygen produced by the incomplete combustion of carbon. It is emitted by automobiles and is the major air pollutant on the basis of weight.

catalytic converter — A device added on the exhaust pipe of an automobile that converts the air pollutants, carbon monoxide (CO) and hydrocarbons, to carbon dioxide (CO_2) and water.

Celsius — See Centigrade.

Centigrade — A temperature scale in which the temperature of melting ice is set at 0°, the temperature of boiling water at 100°. One degree Centigrade is 9/5 of a degree Fahrenheit. The Centigrade scale is sometimes known as the Celsius scale.

char — A porous, solid residue resulting from the incomplete combustion of organic material. If produced from coal, it is called coke; if produced from wood or bone, it is called charcoal. It is more nearly pure carbon than the coal, wood, or bone from which it is produced.

chemical energy — A form of energy stored in the structure of atoms and molecules, and which can be released by a chemical reaction.

classical smog — See sulfur smog.

clean fuel — Usually means fuel in which there is very little sulfur.

coal — A solid, combustible, organic material formed by the decomposition of plant material without free access to air. It is about 75 percent carbon.

coal gas — The volatile, combustible gas driven from coal in coke-making. It has a low energy density, about one-third that of natural gas (also called "fuel gas").

coal gasification — The conversion of coal to a gas suitable for use as a fuel.

coal liquification — The conversion of coal into liquid hydrocarbons and related compounds by hydrogenation, the addition of hydrogen.

coalplex — See combined cycle plant.

coal tar — A gummy, black substance produced as a by-product when coal is distilled.

coke — Degassed coal. A porous, solid residue resulting from the incomplete combustion of coal heated in a closed chamber, or oven, with a limited supply of air. More nearly pure carbon than coal, coke is a desirable fuel in certain industries.

combined cycle electric generating plant — A plant that utilizes waste heat from large gas turbines (driven by gases from the combustion of fuels) to generate steam for conventional steam turbines, thus extracting the maximum amount of useful work from fuel combustion. It may produce fuel (char) as well as electric power.

combustion — Burning. Any very rapid chemical reaction in which heat and light (and sometimes a flame) are produced. Most (but not all) familiar combustions are oxidations — unions with oxygen.

comfort energy — Any form of energy whose end use is the heating and cooling of buildings and homes.

conduction — The transmission of energy directly from molecule to molecule.

convection — The transfer of energy by moving masses of matter, such as the circulation of a liquid or gas.

conversion process — A process by which energy is converted from one form to another, such as radiant energy to heat or electric energy.

cooling towers — Devices for cooling power plants. There are two types: wet towers, in which the warm water is allowed to run over a lattice at the base of a tower and is cooled by evaporation; and dry towers, in which the water runs through a system of cooling fins and is not in contact with the air.

cord of wood — A stack of wood 4 feet by 4 feet by 8 feet. Burned, it produces approximately 5 million Calories of energy.

cracking — Processing that breaks down and rearranges the molecular structure of long hydrocarbon chains in ways that produce lighter hydrocarbons from heavier ones. It is used in the production of volatile fuels, such as gasoline, from crude oil.

crude oil — A mixture of hydrocarbons in liquid form found in natural underground petroleum reservoirs. It is the raw material from which most refined petroleum products are made.

declining block rates — A rate structure in which the charge for energy decreases as the amount consumed increases.

depletion allowance — A Federal tax exemption for a portion of the net income received from producing a natural resource. The amount of the exemption is based on the perceived importance of the energy resource. For oil, gas, and uranium, 22 percent of the income is presently exempted.

deuterium — A hydrogen isotope, the nucleus of which contains one proton and one neutron. (Ordinary hydrogen atoms have only a proton in the nucleus.) About 0.0164 percent of hydrogen occurs naturally as deuterium, which is expected to be the primary fuel for fusion power plants.

distillate oils — Any fuel oil, gas oil, topped crude oil or other petroleum oil derived by refining or processing crude oil or unfinished oils, which has a boiling range at atmospheric pressure from 550 to 1,200°F. Distillate oils account for 25-30 percent of refined petroleum products.

doubling time — The time it takes for a quantity to double.

dry steam — Steam so hot that no water droplets are mixed with it.

efficiency — The efficiency of an energy conversion is the ratio of the useful work or energy output to the work or energy input.

$$E = \frac{\text{work or energy out}}{\text{work or energy in}} \times 100 \text{ percent}$$

electric current — A flow of charged particles, usually electrons (see below).

electron — An elementary particle with a negative charge that orbits the nucleus of an atom. Its mass at rest is approximately 9×10^{-28} gram, and it composes only a tiny fraction of the mass of an atom. Chemical reactions consist of the transfer and rearrangement of electrons between atoms.

electrostatic precipitator — A device that removes the bulk of particulate matter from the exhaust of power plants. Particles are attracted to electrically charged plates and the accumulation can then be washed away.

energy — A quantity having the dimensions of a force times a distance which is conserved in all interactions within a closed system. It exists in many forms and can be converted from one form to another. Common units are Calories, joules, BTUs and kilowatt-hours.

energy density — Energy per unit of weight contained in a fuel.

energy intensiveness (EI) — A measure of energy utilization. For passenger transport, for example, it is a measure of Calories used per passenger mile.

environmental impact statement — Analytical statements that attempt to balance costs and benefits of projects from an environmental as well as economic point of view.

exponential growth — Growth for which the percentage increase for a given time interval is constant. If such growth is plotted on a semilogarithmic graph, in which the vertical axis represents the logarithms of the numbers rather than the numbers themselves, the exponential curve becomes a straight line. A savings account at compound interest is a familiar example.

Fahrenheit — A temperature scale in which the temperature of melting ice is set as 32° and the temperature of boiling water as 212°. One Fahrenheit degree is equal to five-ninths of a Centigrade degree.

fermentation — A process in which carbohydrates are changed to hydrocarbons by the action of microorganisms.

First Law of Thermodynamics — Also called the Law of Conservation of Energy. It states: Energy can neither be created nor destroyed.

fission — The splitting of heavy nuclei into two parts (which are lighter nuclei), with the release of large amounts of energy and one or more neutrons. The emitted neutrons can be absorbed by and initiate fission in other, similar, nearby nuclei, thus producing a chain reaction.

fluidized bed — A furnace design in which the fuel is buoyed up by air or some other gas. It offers advantages in the removal of sulfur during combustion.

force — Intuitively, a "push or pull." Operationally, a non-zero force is defined by the relation $f = ma$ where f is the force, m is the mass, and a is the acceleration of the object. More accurately, the rate of change of momentum of the object.

fossil fuels — Any naturally occurring fuel such as coal, crude oil, or natural gas, formed from the fossil remains of organic materials.

fuel — Any substance that can be burned to produce heat. Sometimes includes materials that can be fissioned in a chain reaction to produce heat.

fuel cell — A device for combining fuel and oxygen in an electrochemical reaction to generate electricity. Chemical energy is converted directly into electric energy without combustion.

fuel gas — See coal gas.

fuel mix — The percentages of various fuels that make up total fuel consumption.

fuel reprocessing — A recycling operation. Fissionable uranium and plutonium are recovered from uranium fuel rods which have undergone intense neutron bombardment in a nuclear reactor.

fusion — The formation of a heavier nucleus from two lighter ones, such as hydrogen isotopes, with an attendant release of energy. The mass of the new, heavier nucleus is less than the combined masses of the original nuclei; the lost mass appears as energy.

gasoline — A refined petroleum distillate composed primarily of light hydrocarbons. Since light hydrocarbons are a relatively small percentage of crude petroleum, most gasoline is produced by refining ("cracking") crude oil. Gasoline has a boiling range at atmospheric pressure from 80°F to 400°F.

generator — A device which produces electric energy from mechanical energy.

geothermal energy — The heat energy in the earth's crust whose source is the earth's molten interior. When this energy occurs as steam, it can be used directly in steam turbines.

gravitational energy — The energy of attraction between two material bodies. Gravitational force is directly proportional to the product of the masses of the two bodies and inversely proportional to the square of the distance between their centers.

greenhouse effect — The warming effect of carbon dioxide, CO_2, in the atmosphere. CO_2 is transparent to incoming sunlight but absorbs and reradiates the infrared (heat) radiation from earth.

Gross National Product (GNP) — A measure of economic activity. GNP is the total market value of all goods and services produced in a country. Depreciation and other allowances for capital consumption are not deducted.

half-life — The half-life of a radioactive element is the time it takes for one-half of a given amount to decay into another element. After two half-lives, one-fourth of the amount remains; after three half-lives, one-eighth remains, etc.

heat — A form of kinetic energy that flows from one body to another because of a temperature difference between them. The effects of heat result from the motion of molecules. Heat is usually measured in Calories or British Thermal Units (BTU).

heat engine — Any device that converts heat energy into mechanical energy.

heat pump — A device that transfers heat from a cooler region to a warmer one by the expenditure of mechanical or electric energy. Heat pumps work on the same general principle as refrigerators and air-conditioners, but are reversible and can pump outside heat in to warm or inside heat out to cool.

heat tax — The heat energy that becomes unavailable for further use whenever energy is converted from one form to another. (See also the Second Law of Thermodynamics.)

heavy water — Water in which all hydrogen atoms have been replaced by deuterium. It is used as a moderator in some nuclear power plants.

high temperature gas reactor (HTGR) — A nuclear reactor which differs from light water reactors in having graphite as a moderator and helium as a coolant. Although not primarily a breeder reactor, thorium 232 can be added to the core and converted into uranium 233 which is a reactor fuel.

horsepower (hp) — A standard unit of power equal to 746 watts.

hydrocarbons — Molecules composed of carbon and hydrogen atoms in various proportions. They are usually derived from living materials.

hydroelectric plant — An electric power plant in which the energy of falling water is converted into electricity by turning a turbine generator.

hydropower — Power produced by falling water.

import quota — Government-set limits on the importation of foreign products.

indirect energy — Any form of energy used in the manufacture of goods or provision of services which themselves may or may not use energy.

intermediate energy forms — Energy in transit from its natural form to the form in which it is useful. For example, energy of coal or falling water (the primary energy form) is converted to electricity (the intermediate form) which in turn is converted to heat energy (the final form) in a radiator.

in situ — In the natural or original position or location. *In situ* production of oil shale, for instance, is an experimental technique in which a region of shale is drilled, fractured, and set on fire. The volatile gases burn off, the oil vaporizes, then condenses and collects at the bottom of the region, from which it can be recovered by a well.

There also has been some experimentation with *in situ* conversion of coal.

ionization — Removal of some or all electrons from an atom, leaving the atom with a positive charge, or the addition of one or more electrons, resulting in a negative charge.

isotope — Any of two or more species of atoms having the same number of protons in the nucleus (or the same atomic number) but with differing numbers of neutrons. All isotopes of an element have the same number of electrons and have identical chemical properties, but the different nuclear masses produce slightly differing physical properties. Since nuclear stability is governed by nuclear mass, one or more isotopes of an element may be radioactive or fissionable, while other isotopes of the same element may be stable. In the usual notation isotopes of the same element are identified by the total of neutrons and protons in the nucleus, for example, uranium 235 and uranium 238.

joule — A metric unit of work or energy; the energy produced by a force of one newton operating through a distance of one meter.

kerosene or kerosine — A mixture of hydrocarbons obtained by the fractional distillation of petroleum and used as a fuel for jet engines and gas turbines. It consists of slightly heavier hydrocarbons than are found in gasoline and naphtha.

kilowatt (kw) — A unit of power, usually used for electric power, equal to 1,000 watts, or to energy consumption at a rate of 1,000 joules per second.

kilowatt-hour (kw-hr) — A unit of work or energy equal to that expended by one kilowatt in one hour. It is equivalent to about 853 Calories of heat energy.

kinetic energy — The energy of motion; the ability of an object to do work because of its motion.

laser — A device that can produce high-intensity, coherent radiation. Coherent radiation or light is produced when the atoms or molecules in a material are forced to radiate at the same time, in step with one another, rather than randomly and independently as in a normal light bulb.

Law of Conservation of Energy — See First Law of Thermodynamics.

life cycle costs — The cost of an item year by year, including initial purchase price as well as cost of operation, maintenance, etc. over the life of the item.

light — Electromagnetic radiation which can affect the eye. The portion of the electromagnetic spectrum considered visible light is wave lengths from approximately 430 millimicrons to 690 millimicrons. (1 millimicron = 10^{-9} meter.)

light water reactor (LWR) — Nuclear reactor in which water is the primary coolant/moderator. They presently use slightly enriched uranium 235 as fuel.

liquid metal fast breeder reactor (LMFBR) — A nuclear breeder reactor cooled by molten sodium in which fission is caused by fast neutrons. It uses uranium 235 or plutonium 239 as fuel and produces additional plutonium 239 from the uranium 238 in a "blanket" around the reactor core.

liquified natural gas (LNG) — Natural gas that has been cooled to approximately −160°C, a temperature at which it is a liquid. Since liquification greatly reduces the volume of the gas, the costs of storage and shipment are reduced.

load factors — The percentage of capacity actually carried. For example, the average number of passengers for a certain size car divided by the passenger capacity of that size car would equal the load factor.

long wall mining — A technique in which an armored mining machine progresses into a seam and allows the ceiling to collapse behind it. This eliminates the necessity of leaving coal behind as pillars, thus substantially increasing the recovery factor.

Lurgi process — A coal gasification process developed in Germany and already in commercial use in Europe. It produces a gas of somewhat lower heat value than natural gas.

magma — Molten rock within the earth's interior.

magnetohydrodynamic (MHD) generator — An expansion engine in which electricity is generated from the combustion of fuels without going through an intermediary steam turbine. Hot, partially ionized gases move through a magnetic field, generating a current that is then collected by electrodes lining the expansion chambers.

marginal cost pricing — The basing of price on the cost of the last unit produced.

mechanical energy — One form of energy. It is observable as the motion of an object.

megawatt (mw) — A unit of power. A megawatt equals 1,000 kilowatts, or 1 million watts.

microwave — Electromagnetic radiation with wavelengths of a few centimeters. It falls between infrared and radio wavelengths on the electromagnetic spectrum.

mine acids — Acids, usually a sulfuric acid formed by the action of water on sulfur left over from coal mining operations.

mine mouth plant — An electric generating plant located at the source of coal and relying on high voltage transmission lines to carry the electricity to distant load areas.

moderator — A material used in a nuclear reactor to slow the speed of neutrons and thus control the rate of fission. Common moderators are graphite, water, deuterium, and beryllium.

molecule — Atoms combined to form the smallest recognizable unit of a substance. For example, the water molecule is composed of two atoms of hydrogen and one atom of oxygen.

natural gas — A naturally occurring mixture of hydrocarbons found in porous geologic formations under the earth's surface, often in association with petroleum. It is almost pure methane, CH_4, but also contains small amounts of various more complex hydrocarbons.

natural gas liquid — Components of natural gas which are liquid at room temperature but become gases at slightly higher temperatures. Propane and butane are examples.

neutron — An elementary particle which is present in all atomic nuclei except for the most common isotope of hydrogen. Its mass is approximately that of a proton, but it has no electric charge. Neutrons are released in fission and fusion reactions.

nuclear energy — The energy released during reactions of atomic nuclei.

nuclear reactor — A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential component is a core with fissionable fuel. It usually has a moderator, shielding, coolant, and control mechanisms.

nucleus — The extremely dense, positively charged core of an atom. It contains almost the entire mass of an atom, but fills only a tiny fraction of the atomic volume.

"off-peak" power — Power generated during a period of low demand.

oil import quota — See import quota.

oil depletion allowance — See depletion allowance.

oil shale — A sedimentary rock containing a solid organic material called kerogen. When oil shale is heated at high temperatures, the oil is driven out and can be recovered.

once-through cooling — Cooling of an electric generating or industrial plant by pumping cold water from a river or lake through the condenser and then discharging the heated water back into the source.

OPEC — The Organization of Petroleum Exporting Countries. An organization of countries in the Middle East, North Africa, and South America which aims at developing common oil-marketing policies.

overburden — The material (soil, rocks, etc.) that overlies an ore or coal deposit. The overburden is removed in strip mining before the coal or ore is mined.

ozone — A molecule containing three oxygen atoms (O_3). It is formed when solar radiation splits an oxygen (O_2) molecule into two oxygen atoms, one of which then combines with another oxygen molecule. At the top of the earth's atmosphere, it acts as a protective layer by absorbing ultraviolet radiation. It is also a major component of photochemical smog; it has a sharp, unpleasant odor and is an eye irritant.

PANS — Peroxyacetyl nitrates, components of photochemical smog formed by the action of sunlight on the nitrogen oxides and hydrocarbons of air pollution.

paramarginal resource — An identified resource that is not recoverable under current economic or technological conditions.

particulates — The small soot and ash particles produced by burning.

peak load — The maximum amount of power delivered during a stated period of time.

permafrost — The permanently frozen subsoil found in colder areas of the world such as northern Canada and Alaska.

petrochemicals — Chemicals derived from petroleum.

petroleum — (or oil) An oily, flammable liquid that may vary from almost colorless to black and occurs in many places in the upper strata of the earth. It is a complex mixture of hydrocarbons and is the raw material for many products.

photochemical smog — Smog produced by the action of sunlight on the pollutants emitted by automobiles. The major components of photochemical smog are ozone and peroxyacetyl nitrates (PANs).

photons — A quantum (the smallest unit) of electromagnetic radiation. It has no mass or electric charge, but behaves like both a particle and a wave in its interactions with other particles.

photosynthesis — The process by which green plants convert radiant energy (sunlight) into chemical potential energy. Carbon dioxide and water are converted into carbohydrates (such as glucose). Carbon dioxide (CO_2) + water (H_2O) + energy = carbohydrates $C_x(H_2O)Y$ + Oxygen (O_2).

photovoltaic process — The process by which radiant energy is converted directly into electric energy. Solar radiation striking certain materials is absorbed, causing separation of electrons from atoms. The migration of these electrons in one direction and of the positively charged ions in the other produces a small potential difference, typically about 0.5 volts.

plasma — A "gas" of charged particles which exists only at temperatures high enough to strip all electrons from atomic nuclei.

potential energy — "Stored" energy. Energy in any form not associated with motion; such as that stored in chemical or nuclear bonds, or energy associated with the relative position of one body to another.

power — The rate at which work is done or energy expended. It is measured in units of energy per unit of time such as Calories per second, and in units such as watts and horsepower.

primary energy — Energy in its naturally-occurring form — coal, oil, uranium, etc. — before conversion to end-use forms.

productivity — The value added to goods divided by the man-hours input.

proton — An elementary particle present in all atomic nuclei. It has a positive electric charge. Its mass is approximately 1,840 times that of an electron.

pumped storage — Reversible pump-turbines use surplus electric power to lift water into a reservoir when demand is low and then use it to generate power when it is needed.

pyrolysis — The application of high temperature to a substance and the resultant transformation of that substance into one or more other compounds.

radioactivity — The spontaneous transformation of an atomic nucleus during which it changes from one nuclear species to another with the emission of particles and energy.

radon — A radioactive gas which is formed by the decay of uranium and other radioactive materials.

recoverable resource — That portion of a resource expected to be recovered by present-day techniques and under present economic conditions. Includes geologically expected but unconfirmed resources as well as identified reserves.

reserve — That portion of a resource that has been actually discovered and that is presently technically and economically extractable.

residual fuel oil — The heavy residue of petroleum that remains after lower boiling fractions are distilled. It is used primarily for generating electricity in industry and large commercial buildings.

resource — The total estimated amount of a mineral, fuel, or energy source, whether or not discovered or currently technologically or economically extractable.

retorting — The heating of oil shale to drive out the oil and gas.

secondary recovery — Recovery techniques used after some of the oil and gas has been removed and the natural pressure within the reservoir has decreased.

Second Law of Thermodynamics — One of the two "limit laws" which govern the conversion of energy. Referred to here as the "heat tax," it can be stated in several equivalent forms, all of which describe the inevitable passage of some energy from a useful to a less useful form in any energy conversion.

solar cell — A device which converts radiant energy directly into electric energy by the photovoltaic process. Each cell produces a small potential difference, typically about 0.5 volts; an array of cells can provide a useful electric power capacity.

solar collector — A device for collecting solar energy and converting it into heat.

solar energy — The electromagnetic radiation transmitted by the sun. The earth receives about 4,200 trillion kilowatt-hours per day.

solar farm — Not yet in existence, these "farms" would consist of an array of solar collectors, a heat transfer system, and electric generating facilities.

solvent refined coal (SRC) — A tar-like fuel produced from coal by dissolving it in a solvent. It is higher in energy value and contains less sulfur or ash than coal.

stored energy — See potential energy.

strip mining — A mining technique used when deposits of coal lie relatively near the surface (less than 100 feet). The overburden (the soil and rock above the coal) is stripped away, the coal removed, and the overburden from a trench dumped in the previous, and parallel, one. Strip mining is used primarily for coal, but may be used extensively in the mining of oil shale as well.

submarginal resource — That portion of a resource that cannot presently be extracted economically. As the economic picture and technology change, some submarginal resources may become recoverable resources.

subsidence — A sinking down of a part of the earth's crust due to underground excavations. If extensive, a cave-in can result.

sulfur smog (classical smog) — This smog is composed of smoke particles, sulfur oxides (SO_x), and high humidity (fog). The sulfur oxide (SO_3) reacts with water to form sulfuric acid (H_2SO_4) droplets, the major cause of damage.

supertankers — Extremely large oil tankers that can hold up to 4 million barrels (170 million gallons) of oil. The largest ones will require deepwater ports.

synthetic natural gas (SNG) — A gaseous fuel manufactured from coal. It contains almost pure methane, CH_4, and can be produced by a number of coal gasification schemes. The basic chemical reaction is coal (C) + $2H_2 \rightarrow CH_4 \pm$ heat.

system efficiency — The cumulative efficiency of a process from the extraction of the natural fuel to the final use.

tar sand — A sandy geologic deposit in which oil is found. The oil binds the sand together.

temperature — Intuitively, the "hotness" or "coldness" of a substance, a measure of the changes which result from heat energy transfer. The temperature of a substance is proportional to the average kinetic energy of its atoms or molecules.

tertiary recovery techniques — Use of heat and other methods to augment oil recovery (presumably occurring after secondary recovery).

thermal energy — Heat energy.

thermal pollution — An increase in water or air temperature which disturbs the ecology of the area. Most often thermal pollution is associated with electric generating plants, which require large amounts of cooling water to remove waste heat.

thermodynamics — The science and study of the relationship between heat and mechanical work.

thermonuclear reaction — A fusion reaction which is initiated by intense heating.

threshold dose — The largest "safe" radiation dosage. Theoretically, no damage would occur below this level. It is not presently possible to determine whether there is a threshold dose or whether any amount of radiation causes some effect.

topping cycle — A means to use high-temperature heat energy that cannot be used in a conventional steam turbine. A gas turbine, for instance, might operate as a topping cycle on furnace gases of 2 000°F and its exhaust could then heat steam for a turbine operating at 1,000°F.

transmission line — A cable or wire through which electric power is moved from electric power generating plants to areas of use by consumers. It usually is operated at greater than 250,000 volts.

tritium — A radioactive isotope of hydrogen in which the nuclei of the hydrogen atoms contain one proton and two neutrons.

tundra — A thin layer of topsoil on top of the permafrost, a permanently frozen subsoil.

turbine — A bladed, wheel-like device which converts the kinetic energy of a gas or liquid into the mechanical energy of a rotating shaft. A motor turned by a stream of fluid or gas under pressure.

ultraviolet radiation — Electromagnetic radiation whose wavelength is somewhat shorter than that for visible light but longer than that for x-rays.

value added — The difference between the value of a delivered product and the cost of the raw materials, labor, and energy to produce it.

voltage — The potential difference measured between two points in an electric circuit. The work per unit charge required to move an electric charge between two points.

water table — The level below the surface at which the ground becomes saturated with water.

watt (w) — A metric unit of power usually used in electric measurements which gives the rate at which work is done or energy expended. One watt equals one joule of work per second.

work — Energy that is transferred from one body to another in such a way that a difference in temperature is not directly involved. The product of an external force times the distance an object moves through its application.

x-ray — Electromagnetic radiation with a very short wavelength (about the diameter of an atom).

APPENDIX 2
A Mathematics Primer

A Mathematics Primer

There are very few mathematical expressions in this Source Book. We have made a determined attempt to use this language sparingly. It is not, however, possible to talk about energy without some numbers and tools of mathematics. We will use this Appendix, therefore, as a primer for those few tools — large number codes, semilogarithmic graphs, exponential functions, doubling times, and rates of growth — which we do employ.

A Code for Large Numbers

In this country, millions of people use millions of tons of coal to generate trillions of kilowatt-hours of electricity. Since one trillion is written 1,000,000,000,000, we can justify using an abbreviation code to save space alone. The code we use is suggested by the written-out form above: One trillion is 1 followed by 12 zeros. Our code is based on this, on powers of 10. We are familiar with the operation of squaring a number and know that 10^2 is 100. The 2 is called the "power" and 10^2 is "ten to the second power." The familiar powers of 10 are: $10^2 = 100$, $10^3 = 1{,}000$ and $10^4 = 10{,}000$. We note that the power is equal to the number of zeros to the right of the 1 and our code is born. (We do have to add, by fiat, that $10^0 = 1$.)

We summarize, in Table A2-1, the range of numbers that occur in this book, expressed first as a power of 10, then as a word, and, finally, in the last column, we give the code used throughout the text.

TABLE A2-1
Large Numbers

Power of Ten Notation	Word	Abbreviation
10^0	one	na*
10^1	ten	na
10^2	hundred	na
10^3	thousand (kilo)**	k
10^4	ten thousand	10k
10^5	hundred thousand	100k
10^6	million (mega)**	M
10^7	ten million	10M
10^8	hundred million	100M
10^9	billion	B
10^{10}	ten billion	10B
10^{11}	hundred billion	100B
10^{12}	trillion	T
10^{13}	ten trillion	10T
10^{14}	hundred trillion	100T
10^{15}	quadrillion	Q

*na, no abbreviation

**The terms in the parentheses are the common prefixes which we will use, kilowatts or megawatts, for instance, meaning thousands or millions of watts.

As an example: the total energy consumed in the United States in 1974 was 18,500,000,000,000,000 Calories or 18 quadrillion, 500 trillion Calories. We write this in power of 10 notation as 18.5×10^{15} Calories. The power, in this case 15, gives the number of places to the right of the decimal point. We could write it equivalently as 1.85×10^{16} Calories or $18{,}500 \times 10^{12}$ Calories. In order to have as concise and consistent a form as possible for these large numbers, we write this figure for total energy as either 18.5 Q Calories or 18,500 T Calories.

We stop our table at a quadrillion, 10^{15}, even though some of our numbers (the total amount of heat energy available from coal resources, for instance) are as large as 10^{18}. We just write that as 1,000 Q.

The power of 10 notation can take us in the other direction also, toward smaller and smaller numbers. For these numbers we use negative powers, which mean reciprocals. One over 10, one-tenth (1/10 or 0.1), is written 10^{-1}; one-hundredth, or 0.01, is written 10^{-2}, etc. Small numbers, however, occur infrequently in this book and we have not set up an abbreviation code for them.

Semilogarithmic Graphs

We use not only the language of mathematics but its visual representations also. Much of the Source Book data is most efficiently shown graphically. Many of these graphs are cast in the same familiar form as the stock market's ups and downs or cost-of-living curves; the vertical axis, which measures the increase (or decrease) of the quantity being studied, has a linear scale. (Each vertical unit, each vertical inch on the scale, for instance, measures the same amount of increase or decrease.)

All data, however, cannot be handled on a simple linear graph. Whenever a quantity changes during the period of concern by more than a factor of 10, we begin to lose detail in presenting it this way. Figure A2-1, for instance, shows the growth in the per capita consumption of electric energy in this country during the period 1890-1970. Consumption increases from about 100 kw-hrs per person to above 8,000 kw-hrs per person over this period. A fault of the linear scale is that details of changes in consumption in the 100-1,000 kw-hrs per person range are not as clearly shown as are those at higher consumption levels. When the same data are plotted on a graph in which the vertical scale is logarithmic, Figure A2-2, these details become more evident.

The basic idea behind the logarithmic scale is as follows: when a quantity spans a wide range, from 10 to 10,000, for instance, and it is desired to emphasize fluctuations between 10 and 100 as strongly as those between 100 and 1,000, then the same amount of vertical space on the scale must be allotted to the 10 to 100 range as to the 100 to 1,000 range. In Figure A2-2, you will notice the vertical distances from 10 to 100, from 100 to 1,000, and from 1,000 to 10,000 are the same.

The "logarithm" accomplishes this allotment. You may remember that the logarithm, say X, of a number N

"to the base 10" is the value of X that satisfies the equation

$$N = 10^x$$

that is, the power to which 10 must be raised to equal the number N. We can see from this equation that the logarithm of 10 is 1 (since $10^1 = 10$), of 100 is 2 (since $10^2 = 100$), and of 1,000 is 3 (since $10^3 = 1{,}000$). Thus, if we plot as equal distances along a vertical scale the *logarithms* $X = 1, 2, 3$, rather than the numbers, we can obtain a scale that greatly compresses the data. All the numerical values between 1 and 10 fall into the first division, those between 10 and 100 into the second, etc. The vertical scale of Figure A2-2 is laid out in this fashion — equal distances are equivalent to equal logarithms rather than equal numbers.

Exponential Functions

An even more important reason for using this "semilog" presentation is that it offers great simplicity in displaying quantities that increase in size "exponentially," as do many of the quantities we study in this Source Book.

When a quantity's net increase over a given period of time depends on its size at the beginning of that period, we say it grows exponentially with time. In mathematical language this is written

$$\frac{\Delta N}{\Delta t} = rN \qquad \text{Eq. A2-1}$$

where N is the quantity which is growing with time, ΔN is the change in N (read Δ, the capital Greek delta, as *"change in"*), Δt the time period, and r is the constant *percentage* increase during Δt. With this formula in view, we can define exponential growth as growth with a constant percentage rate of increase.

A savings account provides a good example of exponential growth. In this example, N is the amount of money in the account at the beginning of the interest period (Δt), r is the interest rate for that period, and ΔN is the amount of interest the account draws.

If N is \$1,000 and r is 6 percent per year, then after a year ($\Delta t = 1$ year) the increase in ΔN

$$\Delta N = rN\Delta t$$

$$= \frac{.06}{\text{year}} \times \$1{,}000 \times 1 \text{ year}$$

$$\Delta N = \$60$$

At the beginning of the next year, $N = \$1{,}060$, and the calculation is repeated. We show, in Figure A2-3, a linear plot of N against t in years. This is an exponential curve in which we see that N grows to \$10,000 after 40 years.

FIGURE A2-1
U.S. Per Capita Consumption of Electricity (Linear Scale)

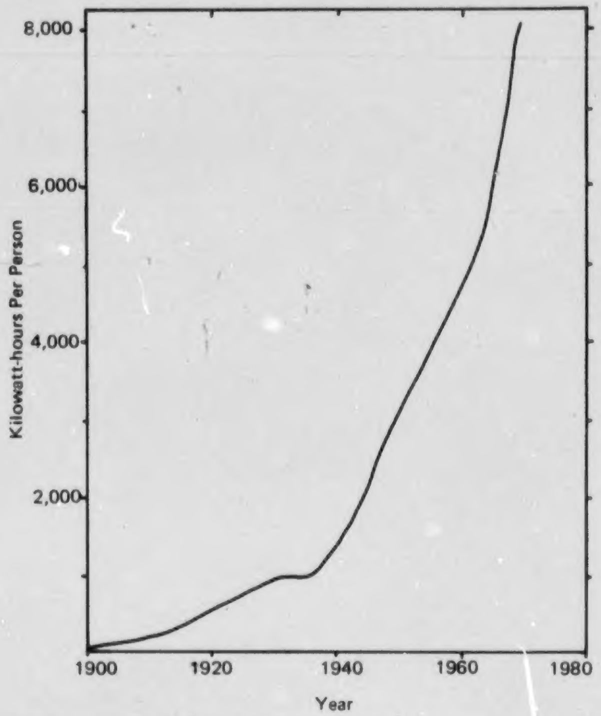
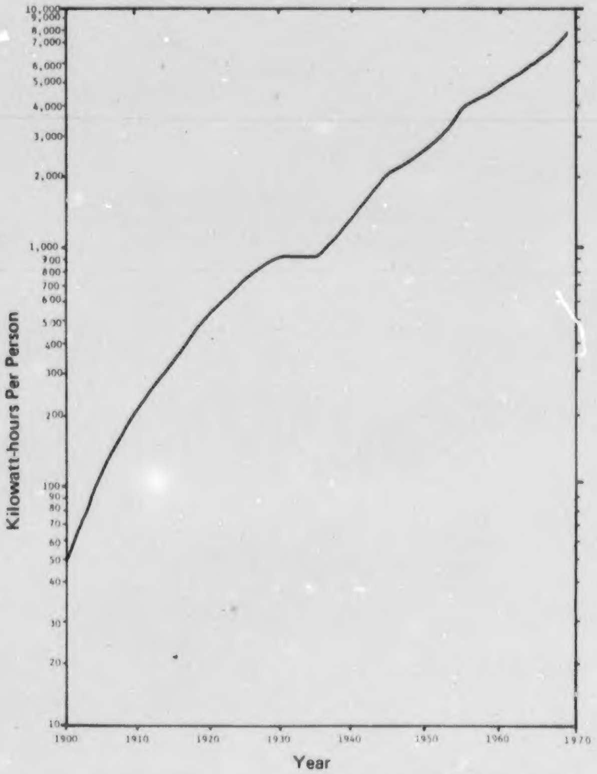


FIGURE A2-2
U.S. Per Capita Consumption of Electricity (Semilogarithmic Scale)



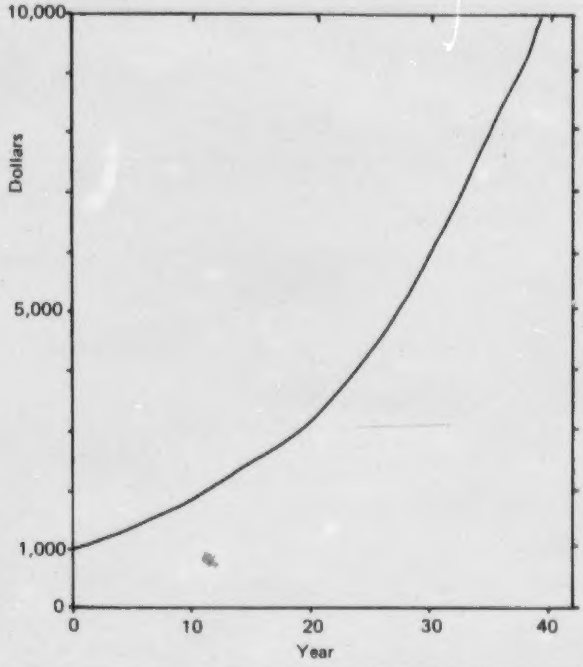
This same data are plotted on semilog graph paper in Figure A2-4. The exponential growth curve on a semilog plot is a *straight line*. The relationship between logarithms and exponentials is such that this has to be, but we will not develop the analysis here. What we need to know is why a straight-line representation of an exponential is important and how it can be interpreted.

A straight line is the preferred representation of a growing quantity because, since it is straight, one can easily project it — can see where it is going. If we project the savings account of Figure A2-4, we see that it reaches $30,000 after 58 years. A curve, such as is shown in the linear plot of Figure A2-3, cannot be projected with such accuracy. A straight line has the significant advantage of being determined by two points, which means it can be extended in either direction by that simple tool, the ruler. We are, therefore, at a considerable advantage in dealing with these exponential curves of growth when we plot them as semilog graphs.

Doubling Time

We can see from the savings account example and from Equation A3-1 that the constant r is of great importance in characterizing exponential growth: it determines how rapid the growth will be. In the case of a savings account, r is the interest, generally, it is the *annual rate of growth*, the annual percentage increase. If r is large, the straight line slopes up more steeply than if it is small. Thus, a savings account with interest r of 10 percent will follow the dotted curve in Figure A2-4 (and that account reaches $10,000 much more rapidly than the one at 6 percent). The annual rate of growth is a most important quantity, and we refer to it often.

FIGURE A2-3
Growth of $1,000 at 6 Percent Per Year (Linear Scale)



A second and related measure of growth is *doubling time*, the time it takes for a quantity to double in size. This is also constant for exponential growth, as we can see from Figure A2-4. The savings account at 6 percent interest doubles in 12 years, doubles again (goes from $200 to $400) in the next 12 years, and continues to double every 12 years. Doubling time, therefore, is 12 years. The doubling time for the account at 10 percent interest is shorter, about seven years. An exponential curve can be defined by the fact that it has a *constant* doubling time.

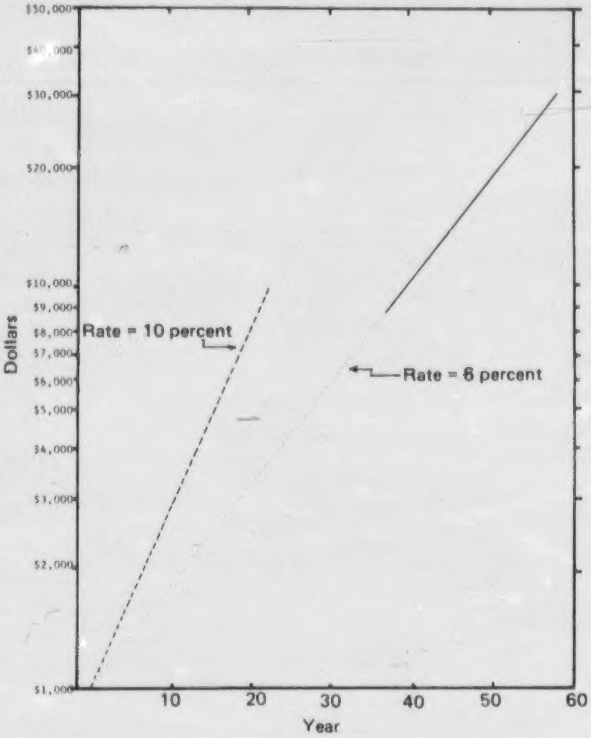
Doubling time is an important quantity in the Source Book, for, as we point out, many of the difficulties of the energy crisis are due to the fact that the doubling time of electric energy consumption is 10 years. Ten years is a short time in which to build the necessary generating plants and other facilities. Annual rate of growth r and doubling time are, of course, related. We will not derive this relationship (although it is a simple exercise in mathematics). An appropriate statement of it is that

$$T_{\text{double}} = \frac{70 \text{ years}}{r \text{ (percent per year)}} \qquad \text{Eq. A2-2}$$

In words, the doubling time in years, T_{double}, is equal to 70 years divided by the annual rate of growth in percent per year. We will leave it to the reader to verify this for the growth curves of Figure A2-4.

The ease with which the doubling time, and therefore the annual rate of growth, can be read off of the straight

FIGURE A2-4
Growth of $1,000 at Indicated Interest Rate (Semilogarithmic Scale)



line, semilog plot of an exponential, is a further reason for using this kind of a representation.

We should not leave this discussion of doubling time without emphasizing what an enormous change a doubling is. As an example, let's take the total energy consumption in this country, which is increasing at an annual rate of about 3.5 percent. From Equation A2-2, we find that the doubling time is about 20 years (70 years ÷ 3.5 = 20 years). This means that during the past 20 years we have consumed as much energy as we did in our entire previous history. In the next 20 years we will again consume an amount of energy equal to the total previous consumption, and so on.

Inflation provides another example. Ten percent inflation means a doubling time of 70 ÷ 10, or seven years. Prices double every seven years.

Proportionality and Equations

This final section of the primer deals with some of the phrases and sentences of mathematics. *Is proportional to* is one of these, it tells us how one quantity depends on another. For example, the area of a circle depends on the square of its radius. If we use A for area and r for radius, the phrase is written

$$A \propto r^2$$

Such a relationship tells us that a circle with twice the radius of another has four times its area, for instance. It does not allow us to compute the area knowing the radius. For that we need an *equation*. To make an equation out of the proportionality we need a constant, which we will symbolize by k, and write

$$\text{Area (circle)} = kr^2$$

We find, of course, in this example, that k is the constant π, which is 3.14159, and obtain the familiar equation

$$A = \pi r^2$$

Knowing π and r, we can compute A. In our earlier savings account equation, the constant was r, the annual rate of interest.

It is this constant that makes the units on either side of the equation match (be the same), as they must. For example, the energy available from gasoline is proportional to the amount of gasoline you have, $E \propto N$ (gallons). To make an equation out of that proportionality we must write it as

$$\text{Energy} = k \times N \text{ (gallons)}$$

The actual numerical value of k depends on the units we desire for energy: if we want Calories, then k = 33,000 Calories per gallon; if we want BTUs, then k = 130,000 BTUs per gallon. If we wish to find the amount of energy in Calories available in a gasoline tank of, say, 10 gallons, we would use the equation

$$E \text{ (Calories)} = 33{,}000 \left(\frac{\text{Calories}}{\cancel{\text{gallons}}}\right) \times 10\,\cancel{\text{gallons}}$$
$$= 3.3 \times 10^5 \text{ or .33M Calories}$$

Note we have treated the units, gallons, like numerical quantities and cancelled them leaving only Calories on the right as units to equal the Calories on the left. This is a handy way of checking to see if we are using the correct units for k.

We repeat in closing this Appendix that you can understand most of the Source Book without the vocabulary we have introduced here. These simple additions, however, can greatly deepen that understanding.

APPENDIX 3

Force, Work, Energy, and Power

Force, Work, Energy, and Power

What is energy? In the beginning of Volume II of this Source Book, we said: "energy is energy." A common definition is that "energy is the capacity to do work." Unfortunately, neither definition is satisfactory; work and energy are both left undefined.

In science, where verbal statements usually have mathematical expression, precision of definition is of primary importance. To gain precision, terms such as energy, force, and work are defined "operationally," that is, by the operation necessary to observe or measure them. In this Appendix we will make some such definitions, review the relationships between these quantities, and provide some of the mathematical expressions which allow us to represent them by numbers. We also provide a table of conversion factors between the various units in which energy and power are measured.

Force, Mass, and Acceleration

We will get at the definition of energy indirectly by linking it with force. Force is an easier concept to understand; you might say we have some "feel" for it.

If asked to define a force, we might say "a push or pull," but this is still not precise. We cannot put numbers in such a statement. The operational definition of a force connects it to the change in velocity, the acceleration, of an object. It was Isaac Newton, the great 18th-century physicist, who gave us this definition in his famous relation

$$f = ma \qquad \text{Eq. A3-1}$$

This equation connects force f to acceleration a (where $a = \Delta v / \Delta t$, the change in velocity Δv divided by the time Δt over which that change took place), the constant in the equation, m, is the mass of the object.

We can measure a by measuring the change in velocity and the time. The operational definition of force therefore, will be complete if we provide a way to measure mass m. Fortunately, this is easy. There are standards of mass ("measure" means, after all, "compare with a standard"). In the scientific system the standard mass is the kilogram, a thousand grams. Thus, to measure mass one compares the unknown mass with the standard using a balance of some sort.

The units of mass and acceleration are kilograms and meters per second per second respectively. Force thus has the units

$$f = ma \text{ (kg} - \text{meters per sec}^2\text{)}$$

We define a unit of force, the newton, as 1 kg × 1 m/sec^2 or, equivalently, a force of one newton will cause a one-kilogram mass to increase its velocity one meter per second each second. This is a satisfactorily precise definition of force.

To use a familiar example, a mass near the surface of the earth feels a force on it which we call its *weight*. (The weight is, of course, the pull of the earth's gravity on the object.) This force is defined as

$$f = mg \qquad \text{Eq. A3-2}$$

where m is mass as before and we use g for the *acceleration of gravity*, 9.8 meters per second^2. A 1 kg object, therefore, weighs 9.8 newtons. In the (soon to disappear) English system, weights are in pounds. The rule for conversion from one to another is

$$1 \text{ pound} = 4.45 \text{ newtons}$$

Force, Work, and Energy

We need now to connect the concept of force to the more abstract concept of energy. We do have some intuitive comprehension of energy; we avoid moving cars, stay out from under lifted pianos, and move away from the front of bent bows. In all these examples a familiar object has had something added to it which makes it different; the car because it is moving, the piano because it is lifted, the bow because it is bent. This added quantity is energy.

In Chapter 1, Volume II, we describe the two kinds of energy: *kinetic energy*, the energy of motion; and *potential*, or stored energy. In our examples the car has kinetic energy, the lifted piano and bent bow have potential energy. From the relationship between these two energy forms in the familiar example of a falling body, we can gain some insight into the relationship between force and energy.

Suppose we drop a ball of mass m from a distance h above the ground. Just before it strikes the ground it has an amount of kinetic energy

$$KE = 1/2\, mv^2 \qquad \text{Eq. A3-3}$$

(Equation A3-3 is the general expression for kinetic energy.)

Where did this kinetic energy come from? Clearly, it was stored in the ball by the action of lifting it the height h. Already we see the necessary involvement of a force; it took a force to lift the ball. We can make the relationship precise by inserting into Equation A3-3 the velocity v in terms of the acceleration of gravity g and the height h. This is

$$v = \sqrt{2gh}$$

or

$$v^2 = 2gh^*$$

Inserting this expression for v^2 into Equation A3-3 gives

$$KE = mgh$$

---

*This expression can be found by simple calculus from the relationship between the acceleration and the velocity.

On the left we have the kinetic energy, on the right a term that involves a force *mg* (the *weight*, see discussion of Equation A3-1) and the distance *h*. This term must be the potential energy (the kinetic energy must equal the potential energy, according to the First Law of Thermodynamics — see discussion in Chapter 1, Volume II). Thus the potential energy of an object of mass *m* lifted a height *h* is increased by the amount of *mgh*.

The potential energy is the product of a force times a distance. To store this potential energy we had to exert a force (we'll call it the lifting force) throughout that distance *h*, and that lifting force had to oppose the force of gravity.

In every case of stored energy we investigate, we find the same factors: a force must operate against an opposing force. The application of this force over a distance is what we call *work*. It is this work that produces the change in potential energy which occurs in lifting the object. It is also work that produces the change in kinetic energy when the object is dropped. In that case, the force is the gravitational force itself, acting over the distance *h*, pulling the mass back to earth. In the first instance we did work, in the second the earth's gravity did the work.

The computation of the work, the product of force times distance, is relatively easy when the force is constant and in the same direction as the motion. If, however, either of these conditions is altered the computation of the work becomes more complicated (and we leave it to physics texts).

Work as the Change in Energy

We are much concerned in this book with energy conversions. Since we know that energy is neither created nor destroyed, its use must be through conversion. Work is the name we give to a large class of those conversions, those which are to, or from, mechanical forms. Thus we do work in lifting the object we have been describing and in so doing convert mechanical energy to gravitational potential energy. We obtain work from an electric motor, which converts electric kinetic energy to mechanical kinetic energy. Work is characterized, as we have seen, by the operation of a force over a distance. If the system supplies the force, as in the falling body case, then work is done *by* the system. If the force is supplied externally, by a man lifting the objects, then work is done *on* the system. The final result of the investment of work, on or by a system, is a change in the energy of at least that part of the system on or by which the work is done.

We can make a further very important point about energy storage before we leave it. Consider the lifting force we had to apply to store potential energy in the lifted mass. We treated it as if it were equal to the force of gravity. In fact, however, it must be a little greater than the weight *mg* if it is to cause the mass to move. Thus the energy expended (the work done, since it is the product of the lifting force times *h*) is a little *greater* than the stored potential energy *mgh*. This extra work is the "heat tax" we introduced in Chapter 1, Volume II. It does not go into potential energy. It goes instead into heat, frictional heat with air and energy that is converted to heat in our arm muscles (or somewhere) when we stop the object at the height *h*. In every case of stored energy we might consider — in the charging of a battery, for instance — the force that causes the storage must be a little larger than the force it opposes, and the extra energy pays the heat tax.

Work Against Dissipative Forces

We have so far considered work done in storing energy. Much work is done also just to move things around. In this case there are also opposing forces that use up the work. We call these "dissipative forces." We will not try to either list or describe all the various important dissipative forces, only to make some general statements about them. Most of these dissipative forces oppose motion. The most common example is friction — caused by the adhesive forces between solid surfaces in contact. The result of moving an object against this force is to convert work to heat energy. Another example is air resistance, a complicated resistance to motion that depends on the velocity of the moving object. Again the kinetic energy is converted to heat energy. Other important dissipative forces are the one due to electrical resistance (which we will discuss in Appendix 5) and the more sophisticated force which opposes the motion of electric conductors in magnetic fields.

It is these dissipative forces which are, for the most part, responsible for the heat tax on energy conversions and for the eventual downhill run of all forms of energy to heat energy.

The Three Basic Forces

We have now provided the link between force and energy. In order to change the energy of an object we must apply a force over a distance and either move it — thus giving it kinetic energy — or change its state in some way to give it potential energy. In this latter application, the storage of energy, the force works against an opposing force.

This relationship between force and energy provides a great simplification of the forms of potential energy. There are only three basic forces in the universe, the gravitational force, the electrical force, and the nuclear force. Thus, since we must work against one or the other of these to store potential energy, there can be only three kinds of potential energy in the universe, gravitational potential energy, electrical potential energy, and nuclear potential energy.

We can rate these forces by their strengths. The gravitational force is by far the weakest. We must deal with very large masses — mountains or the earth or the sun — before we notice its effects.

The electrical force is next in size. It is about 10^{36} (a 1 and 36 zeros) times stronger than the gravitational force. It is the most important force on a man-sized scale. It holds atoms and molecules together and is thus responsible for most of the secondary forces familiar to us: the forces of springs and rubber bands, surface tension, friction, adhesion, air resistance, and so on. It should be clear that the dissipative forces are almost all electrical in nature.

The strongest force is the nuclear force. We don't know as much about it as we do about the other two, but it has to be stronger than the electrical force because it holds a nucleus full of protons together. (Since protons are alike they electrically repel each other.)

The potential energies that derive from the gravitational and nuclear forces are fairly obvious. The energy of water lifted to a mountaintop by air currents is gravitational potential energy. The energy released in fission or fusion comes from nuclear potential energy. It is the electrical force that provides the greatest variety. The energy stored in coal, oil, natural gas, or wood is electrical potential energy. (We call it "chemical energy" in Chapter 1, Volume II, but that means the same thing.) The energy of a stretched string, a bent bow, or a charged battery is also electrical potential energy stored in the molecular changes in the substance. Nuclear energy powers the sun and stars, gravitational energy is stored in the great masses of the universe, but electric energy shapes and fuels the world of man.

Units

We have defined force, work, and energy. In Chapter 1, Volume II, we defined that other important quantity, *power,* as the work done per unit time, or symbolically

$$P = \frac{W}{t}$$

None of these definitions are complete, however, until we discuss units. These tell us the size of the "measuring stick" we are using, whether we have a foot ruler or a yardstick, to carry out the analogy. Since work is defined as the change in energy, both work and energy are expressed as force times distance. In the metric system, force is in newtons and distance in meters; the unit of work is newton-meters and is called a *joule*, after the Scottish physicist, James Joule, who did much to establish the Law of Conservation of Energy. A 50 kg woman (weighing 490 newtons, or 110 pounds) who lifts herself a vertical distance of 6 meters (about 20 feet) by walking up a flight of stairs will do 2,940 joules of work.

In the English system of units, force is in pounds, distance in feet, and the unit of work is foot-pounds. In these units the woman does about 2,200 foot-pounds[*] of work.

Since work can bring about changes in other forms of energy and can in turn be derived from conversion of other forms of energy, other units are often employed in the discussion of work and energy. The most important of these are the units by which heat energy is measured: the Calorie and the British Thermal Unit (BTU), and the electric energy unit, the kilowatt-hour. This latter unit is obtained by multiplying a unit of power by a time. There is similar variety in the units of power. Since power is work or energy divided by time, obvious units are joules per second or foot-pounds per second.

The most familiar unit of power is the horsepower, which is roughly the rate at which a horse can work for an extended time. The definition now has been made more precise: one horsepower is defined as 550 foot-pounds of work per second. Thus, in the example of the woman climbing the stairs, if she made it up the 20-foot flight in 10 seconds, she would have operated at just under one-half horsepower. If, however, she raced up them in 5 seconds, her output would have been almost one horsepower.[*]

The unit of power used in this Source Book is the watt, the name given (in honor of James Watt, who contributed so much to the understanding of the steam engine) to the power unit, one joule per second. It is applicable to any measurement of power. One horsepower, for instance, is equivalent to 746 watts of power. The watt, and its larger brother, the kilowatt (1,000 watts) are most often used, however, to measure electric power (which will be discussed in a later appendix).

In order that you can move easily among the many units in which the energy-environment crisis is described, we provide, in Table A3-1, definitions of all the commonly used units of energy (work) and power, and, in Tables A3-2 and A3-3, the appropriate rules for converting one to another.

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[*] 2,940 joules divided by .305 m/ft divided by 4.45 newtons/lb = 2,166 ft-lbs.

[*] a) 2,166 ft-lbs/10 sec = 217 ft-lbs/sec
horsepower = (217 ft-lbs/sec) × (1 H.P.) / (550 ft-lbs/sec) = 0.4 H.P.
b) 2,166 ft-lbs/5 sec = 433 ft-lbs/sec
horsepower = 433/550 = .79 H.P.

TABLE A3-1
Commonly Used Units of Energy and Power

Energy Units	Definitions
*Calorie (or kilocalorie)	The amount of heat energy needed to raise the temperature of 1 kilogram of water 1 degree Centigrade (see Appendix 4).
BTU (British Thermal Unit)	The amount of heat energy needed to raise the temperature of 1 pound of water 1 degree Fahrenheit (see Appendix 4).
foot-pound	The energy required to lift a 1-pound weight 1 foot.
joule	The energy supplied by a force of 1 newton applied for 1 meter (see definition of newton in text of this appendix).
watt-hour	The energy supplied by 1 watt of power in 1 hour (see definition of watt under Power, this appendix).
*kilowatt-hour	10^3 or 1,000 watt-hours.
horsepower-hour	The energy supplied by 1 horsepower of power in 1 hour (see definition of horsepower, this appendix).
Power Units	
horsepower	A time rate of energy expenditure of 550 foot-pounds per second.
watt	A time rate of energy expenditure of 1 joule per second (see also Appendix 5).
*kilowatt	10^3 or 1,000 watts (see Appendix 5).

* Denotes those units we use most frequently.

TABLE A3-2
Conversions—Energy Units

In One	There Are	
Calorie	4	BTU
Calorie	3.1×10^3	foot-pounds
Calorie	4,200	joules
Calorie	1.16×10^{-3}	kilowatt-hours
Calorie	1.6×10^{-3}	horsepower-hours
BTU	0.25	Calories
BTU	780	foot-pounds
BTU	1,055	joules
BTU	2.9×10^{-3}	kilowatt-hours
BTU	2.9×10^{-3}	horsepower-hours
foot-pound	3.2×10^{-4}	Calories
foot-pound	1.3×10^{-3}	BTU
foot-pound	1.4	joules
foot-pound	3.8×10^{-7}	kilowatt-hours
foot-pound	5.1×10^{-7}	horsepower-hours
kilowatt-hour	860	Calories
kilowatt-hour	3.4×10^3	BTU
kilowatt-hour	3.6×10^6	joules
kilowatt-hour	2.7×10^6	foot-pounds
kilowatt-hour	1.35	horsepower-hours
horsepower-hour	640	Calories
horsepower-hour	2.5×10^3	BTU
horsepower-hour	2×10^6	foot-pounds
horsepower-hour	2.68×10^6	joules
horsepower-hour	.75	kilowatt-hours

TABLE A3-3
Conversions—Power Units

In One	There Are	
kilowatt	1,000	watts (joules per second)
kilowatt	740	foot-pounds per second
kilowatt	.24	Calories per second
kilowatt	.96	BTUs per second
kilowatt	1.3	horsepower
horsepower	550	foot-pounds per second
horsepower	.75	kilowatt
horsepower	.18	Calories per second
horsepower	.71	BTUs per second

APPENDIX 4
Heat and Heat Engines

Heat and Heat Engines

Although we rarely think about it, it is a near miracle that we can burn a fuel and use the heat energy to cause an engine to turn. It is that "miracle" we analyze in this Appendix. We begin with a consideration of the remarkable form of energy we call heat. As always we must first establish a vocabulary for its description and lead off with *temperature*, for it is clear that the concepts of hot and cold are somehow related to heat energy.

Temperature

We can distinguish between hot and cold objects by feel, and can easily rank a group of similar items from hottest to coldest. If we are to use the hot-cold concept scientifically, however, we have to measure — to put numbers with it. For that purpose we need to find some material that undergoes a distinctive change in property (in color, length, or electrical resistance, for instance) as it becomes hotter or colder, and use it to construct a "thermo-meter." Mercury, the liquid metal, fills the bill. Confined in a small-diameter transparent tube it responds to temperature change by expanding or contracting. These changes in height can be calibrated to give numerical values to the temperature. This is the common mercury thermometer.

The numerical calibration is, of course, the key. We must establish a temperature scale. Two reference temperatures and a decision on the size of the divisions are needed.

There are two common numerical scales now in use, the *Fahrenheit* scale and the *Centigrade** scale. For the Fahrenheit scale, the two reference temperatures originally chosen were: zero degrees Fahrenheit (0°F) as the temperature of a mixture of salt and ice (and water); 100°F as the temperature of the normal human body.

The choices of reference temperatures of the Fahrenheit scale were not good ones as neither temperature is precisely determined. The choices for the Centigrade scale were more successful: zero degrees Centigrade (0°C) was established as the freezing point of water; 100°C as water's boiling point (both at atmospheric pressure). The Fahrenheit scale was eventually standardized to the same points, so that now, in degrees Fahrenheit, water freezes at 32°F and boils at 212°F.

The relationship between these two scales is shown in Figure A4-1. From this figure we see how to convert from one scale to another. There are 180 Fahrenheit degrees between the freezing point and the boiling point of water, and 100 Centigrade degrees between the same reference points. Thus, the desired Centigrade temperature will be represented by 100/180, or 5/9, as many degrees as the Fahrenheit interval. If the Fahrenheit temperature is 122°F, then the interval is 122° minus 32°, or 90°F. The desired Centigrade temperature, T_C, is, therefore,

$$T_C = 5/9\,(T_F - 32)$$

or

$$T_C = 5/9 \times 90 \qquad \text{Eq. A4-1a}$$
$$= 50^\circ\text{C}$$

To find a Fahrenheit temperature T_F given a Centigrade one, we work backward. If the Centigrade reading is 80°, the T_F is 9/5 × 80, or 144°F above the freezing point. The Fahrenheit temperature is, therefore, 144 + 32 = 176°F. Symbolically,

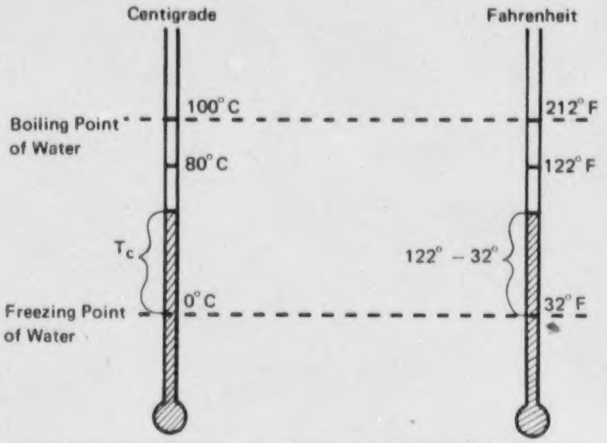
$$T_F = 9/5\,(T_C) + 32$$
$$= 9/5\,(80) + 32$$
$$= 176^\circ\text{F} \qquad \text{Eq. A4-1b}$$

Heat Energy and Hot Gases

With the concept of temperature in hand, so to speak, we can now attack the concept of heat energy. It was the English physicist, Joule, who demonstrated the exact equivalence between mechanical energy and heat energy, and also the equivalence between electric energy and heat energy. Through many experiments he verified that there are fixed "exchange rates" between the different energy forms, in much the same manner that there are fixed exchange rates between the currencies of different countries. In other words, he demonstrated that heat and electricity are forms of energy in the same way dollars and francs are forms of money.

Heat, however, occupies a unique role in the energy picture. An amount of energy of one form can be *entirely* converted to an equivalent amount of heat energy, but a

FIGURE A4-1
Comparison of Centigrade and Fahrenheit Temperature Scales



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*Also called the Celsius scale.

given amount of heat energy *cannot* be entirely converted to another form of energy, such as mechanical energy. This is one way of stating the *Second Law of Thermodynamics*. It is this law of nature that prevents us from creating an electric power plant that is 100 percent efficient; one that converts *all* the energy of its fossil fuel into mechanical energy to drive a turbine, which can in turn drive a generator to produce electricity.

In order to appreciate this unique role of heat energy, we need to examine nature with a magnifying glass to see heat energy as it appears at the molecular level.

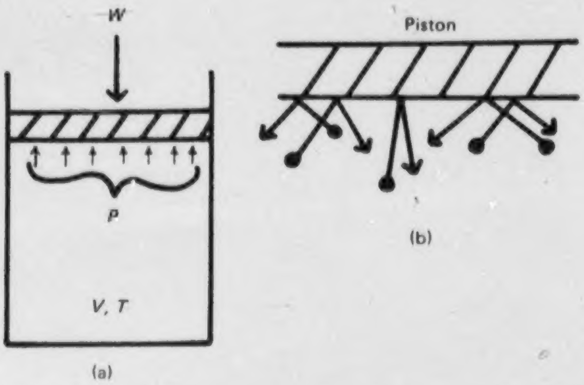
Although the study of heat energy and molecular motion is a fascinating and full subject, we will leave most of it to the physics class and concentrate our attention on hot gases. It is in such gases as steam or the combustion products of gasoline that the conversion of heat energy to mechanical energy takes place.

Those properties of gases which are important for our purposes can be described in terms of a fairly simple model. Although a gas is a collection of weakly interacting molecules, we will think of these molecules as little steel balls bouncing off of each other and off the container's walls. We can explain the role of the three important properties of gases — *volume, pressure,* and *temperature* — in terms of this model.

The unique feature of a gas is that it has no definite volume, it expands to fill any container. An appropriate container for our purposes is the cylinder-piston arrangement of Figure A4-2.

In the arrangement of Figure A4-2a we know that the piston, which has a certain weight W, will compress the gas to a certain volume V and, at that volume (and temperature), the gas will exert a force that balances W. This force is provided by the pressure of the gas. What is pressure? It is defined as a force per unit area, $P = F/A$. It is used when the force is not exerted at a single identifiable point (by a rope or a rod, for instance), but instead force is exerted at all points over a surface, a condition that occurs when we deal with gases or liquids. In the example of Figure A4-2a, therefore, if the cross-sectional area of the piston is A, then the total force exerted by the gas is $P \times A$, and it must equal the weight W if the piston is balanced.

FIGURE A4-2
Molecular Model of Pressure on Piston

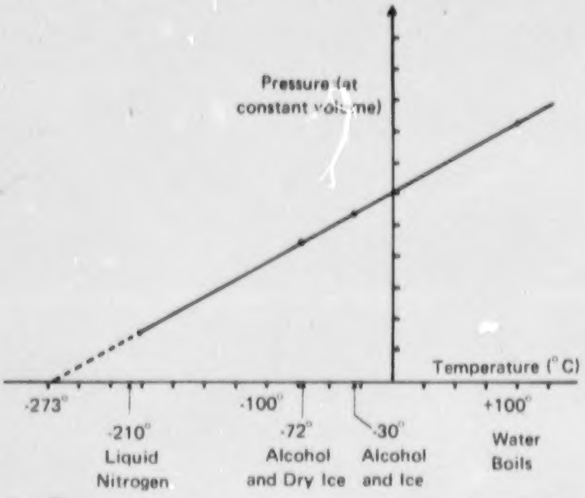


The difference between a pressure and a force is perhaps best shown by the difference between the pressures in bicycle tires and automobile tires. Two bicycle tires support a force (weight) of 200 pounds when inflated to a pressure of 60 pounds per inch^2. Four automobile tires support a force (weight) of 4,000 pounds when inflated to a pressure of 25 pounds per inch^2. We leave it to the reader to find out what *area* of these tires must be in contact with the ground in order to produce the necessary forces.

How does a gas exert pressure? Remembering our simple model of the gas — molecules constantly in motion, colliding with each other and the walls — we can answer: The molecules also collide with the piston — uncountable numbers of them per second. When an object bounces off another object it exerts a force on it — a fact of common observation. Each molecule that collides with the piston, as in Figure A4-2b, exerts a force on the piston. The effect of the steady barrage of molecules is, therefore, an average force on each unit area — a pressure. The total force is, as we have already said, the product of this pressure and the total surface area. The pressure exerted by a gas depends on the number of molecules, on the mass of each molecule (heavier molecules can exert more force), and on their velocity (the faster they are going, the more force they exert upon impact).

Pressure and volume are now defined with respect to the model, where does temperature fit in? The temperature of a gas is proportional to the average kinetic energy of the gas molecules. Since the kinetic energy is given by $KE = 1/2\,mv^2$ (see Equation A3-3, Appendix 3) — that is, it depends on v, the velocity — the molecules move faster as the gas warms up.

FIGURE A4-3
Relationship Between Gas Pressure and Temperature (constant volume)



This relationship between temperature and kinetic energy hides a condition of the temperature we must now make explicit. It should be clear, upon reflection, that temperature can no longer be defined arbitrarily as it was in the previous section. Kinetic energy is a specific quantity that is always positive — we can't use negative temperature.

The temperature scale we will use in the rest of this discussion will be the "absolute temperature scale." This is a scale for which zero is "absolute zero." What we mean by absolute zero can be made clear with the help of Figure A4-3.

Suppose we take a simple gas like nitrogen, confine it in a container (fixed volume), and then change its temperature and record its pressure. The solid straight line of Figure A4-3 would result. At some point most gases become a liquid (nitrogen at −210°C) and the straight-line relation ceases. If, however, we extrapolate that line to zero pressure, it intersects at −273°C. The remarkable fact is that all gases, even though their straight lines have different slopes, intersect at this same temperature. This point, where the pressure of an ideal gas becomes zero, is absolute zero. Since the pressure of the gas depends on the motion of the molecules, this implies that molecular motion ceases also at that temperature and, therefore, that the kinetic energy becomes zero. Absolute zero, of course, is a *limiting* temperature, it can't be reached. Helium, however, liquifies within a degree or so of −273.2°C. It is only for a temperature scale with zero at −273.2°C (or equivalently at −459.7°F) that the proportional relationship between T and $K.E.$ holds.

With this new temperature scale in use, the behavior of the pressure, volume, and temperature of a simple gas is summed up in the equation

$$\frac{PV}{T} = \text{constant} \qquad \text{Eq. A4-2}$$

This tells us all we need to know for our purposes. We will look at one or two instances just to make the operation of Equation A4-2 clear.

Suppose we hold the temperature constant and reduce the volume. This could be accomplished with the apparatus of Figure A4-2 by pushing the piston farther into the cylinder. What happens to the pressure? By Equation A4-2, if T is constant and V decreases, then P must increase if the total is to remain constant.

Alternately, we might hold V constant and increase the pressure (by pumping more gas into the cylinder, for instance). In this case the temperature must increase along with the pressure in order to keep the entire term constant. We see this relationship demonstrated whenever we pump up a tire.

The most important consequence of Equation A4-2 as far as heat engines are concerned results from holding P constant and increasing T — by building a fire under the cylinder, for instance. In this case V must increase — the piston must move and work is performed.

Work from Heat

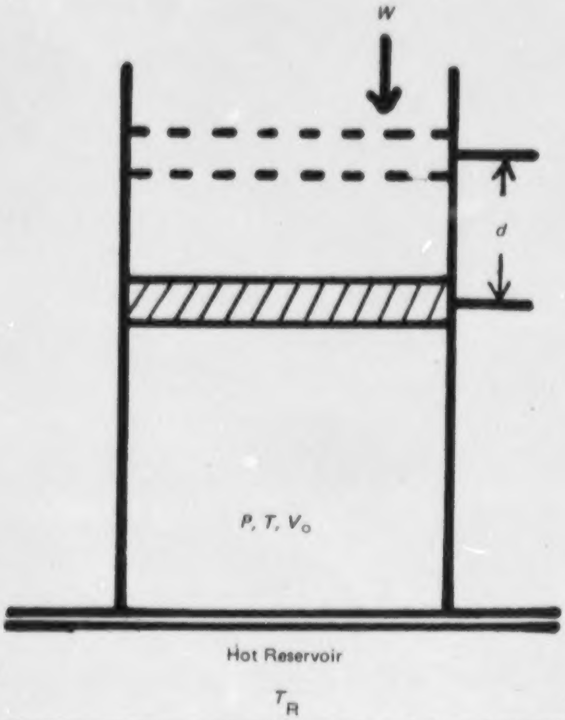
The fundamentals of an engine are shown in Figure A4-4. A gas at a pressure P, temperature T, and occupying a volume V, is put into thermal contact with a "hot reservoir," which is any large source of heat energy (like a steam boiler, for instance) that can continue to supply energy without changing its own temperature.

If the temperature of the cylinder (T_R) is greater than the temperature of the gas in the cylinder (T), then heat energy will flow into the gas, increasing its kinetic energy and, thus, the temperature of the gas. Since the piston is free to move, its weight keeps the pressure constant and, as we saw earlier, the result is that the piston moves upward increasing the volume. That work is done becomes obvious when we see that a force — the pressure times the area A of the cylinder — operates over the distance d.

This work comes from the heat energy provided by the hot reservoir. It is transmitted by the molecules bouncing off the piston. Since the piston is moving away from them when they hit it, they bounce off with a lower velocity than they came in with and thus carry away less energy than they came in with.

In this example all the heat energy was converted to work. This seems to violate the Second Law of Thermodynamics as we stated it earlier. The Second Law, however, applies to a complete cycle, not a simple, one-step operation as we have just considered. It is necessary, if we are to have an engine, to bring the gas

FIGURE A4-4
Work Performed by an Expanding Gas



(the "working fluid") back to its original condition so the cycle can be repeated. In the simple cycle we could push the piston back down, doing work and heating up the gas. The extra heat energy would then go back into the reservoir and we would have obtained no net work. A more complex cycle is needed.

The Perfect Cycle

Figure A4-5 shows an idealized four-cycle engine. It is for this engine that the efficiency equation of Chapter 3, Volume II, is derived. The operation of this "perfect" engine is as follows.

Step A — The gas (it can be steam or air or a mixture of combustion products) expands as heat energy is transferred from the hot reservoir to the gas.

Step B — The cylinder is removed from the heat source and placed on an insulated stand. The weight on the piston is reduced slightly and the gas continues to expand, doing work at the expense of its internal energy. Its temperature drops to the "exhaust temperature" T and, due to the collisions with the piston, the kinetic energy of the molecules decreases. The molecular collisions keep the piston moving.

Step C — The cylinder is now put into contact with a cold reservoir at temperature T_{out}. Gas heat energy now flows from the gas to the lower temperature cold reservoir. The molecules transfer some of their kinetic energy to the cold reservoir and, as a result, the gas volume decreases. The piston is performing work *on* the gas. This is an energy-wasting step, but clearly necessary if the piston is to get back to its initial condition so that it can repeat the cycle.

Step D — The cylinder is moved again to the insulated stand. The weight on the piston is now increased, allowing the compression to continue. During this step work is done on the gas, but, since no heat flow is allowed, this work increases the internal energy and, therefore, the temperature of the gas. At that point, the cycle's end, the pressure has returned to its original value and the temperature is at T_{in}; the process can be repeated.

The efficiency of this engine cycle is given by

$$\text{efficiency} = \frac{\text{energy out}}{\text{energy in}} \times 100 \text{ percent}$$

The useful energy out is, of course, the work; the only energy input is the heat which flowed in from the hot reservoir. Therefore,

$$\text{efficiency} = \frac{W_{out}}{Q_{in}} \times 100 \text{ percent}$$

Heat energy Q_{in} was put in during Step A and some heat energy Q_{out} was rejected during Step C. Since this is an ideal machine (no friction or heat leakage), the work done must be the difference between these two (since energy must be conserved). Therefore,

$W_{out} = Q_{in} - Q_{out}$ and the efficiency is,

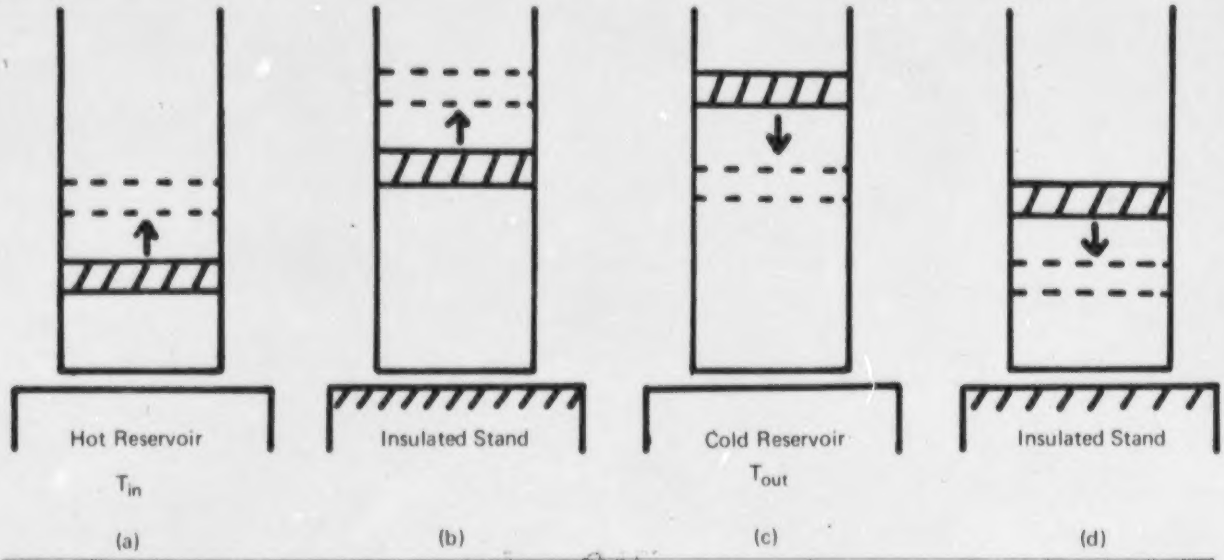
$$\text{efficiency} = \frac{Q_{in} - Q_{out}}{Q_{in}} \times 100 \text{ percent}$$

or

$$= 1 - \frac{Q_{out}}{Q_{in}} \times 100 \text{ percent}$$

The next step is a big one. We won't derive it but only argue for its plausibility. The question is, what can the heat input and output, Q_{in} and Q_{out}, depend on? There is only one property available, the temperature of the reservoirs. Since we have seen earlier that the amount of

FIGURE A4-5
Heat Engine



heat transferred depends on the temperature difference, we set the *Q*s proportional to the *T*s; that is, $Q_{in} / Q_{out} = T_{in} / T_{out}$, and write:

$$\text{efficiency} = 1 - \frac{T_{out}}{T_{in}} \times 100 \text{ percent} \qquad \text{Eq. A4-3}$$

where T_{out} is the exhaust temperature and T_{in} the input temperature.

The fact that this cycle is reversible, that it can run backward using the work to lift heat from the cold to the hot reservoir, is due to its ideal nature; there are no losses due to friction, leakage, etc. It is this reversibility that makes it the "perfect engine." Carnot stated and proved that, in fact, no heat engine operating between the same two temperatures, T_{in} and T_{out}, can be *more* efficient than this "perfect engine." All real engines operating through the same temperature drop will have lower efficiencies. Such real engines are discussed in Chapter 3 of Volume II.

We see from this discussion that 100 percent efficiency is not possible. Even for the perfect engine which we have hypothesized, it is not possible to obtain $T_{in} = 0$ (for this is absolute zero) or T_{out} = infinity. It is because some heat energy must be rejected in Step C that heat engines are intrinsically inefficient. We are stuck with this inefficiency as long as we have to rely on heat engines to convert fuel to work.

APPENDIX 5

Generation, Transmission, and Distribution of Electricity

Generation, Transmission, and Distribution of Electricity

In Chapter 1, Volume II, we identified three intermediate forms of energy, thermal, mechanical, and electric. The first two of these are also important end uses of energy — most of the energy we use is in one or the other of these forms. Electric energy, however, is uniquely intermediate; it is energy in transit and must be converted to another form to be used. Electric energy is *kinetic energy* that is obtained when electric charges are set into motion by electric forces, just as mechanical kinetic energy is obtained when mass is set in motion.

We begin this Appendix with a vocabulary for electricity. We define the terms charge, current, voltage, and resistance with which electric energy and power are discussed. From these definitions we go on to discuss generation, transmission, and distribution of electricity.

Vocabulary of Electricity

Electric Charge

Electric charge resists verbal definition as tenaciously as does mass or any other of the fundamental quantities of science. It must be defined operationally as that quantity which gives rise to measurable electric forces and electric currents just as mass gives rise to gravitational force and momentum.

Electric charge differs qualitatively from mass in two important ways: 1. there are two kinds of electric charge — thus the electric force can be either repulsive or attractive; 2. electric charge is "quantized" — it comes in chunks.

Although the two kinds of charge are called positive and negative, they could have been called black and white, or male and female, or any other set of names which would have underlined their oppositeness. Positive and negative are convenient choices, since in combination the two can cancel, as happens in most bulk matter.

The most important carrier of negative charge is the electron, the elementary particle that is present in the outer "shell" of the atom and determines its chemical properties. The most important positive charge carrier is the proton, the nuclear "building block" that is 1,840 times as heavy as the electron. Protons along with uncharged, but massively similar, neutrons make up the nucleus — the core of the atom.

The proton and the electron have equal amounts of charge, even though there is the fundamental difference in quality — positive and negative. A series of experiments has shown that this amount is, in fact, the smallest amount of charge that exists in nature, and that all other charges are multiples, 1,2,3,4...etc., of the charge of an electron.

Charge can be measured in many different units. It could be measured in electron charges — a charge of 1,2, or 10^{24} electrons, for instance, but the smallness of this charge unit makes this impractical. We normally have to deal with too many electrons. The unit we will use is the *coulomb*, named after Charles Coulomb, whose experiments led to the measurement of electric charge. The coulomb is a large unit of charge: the spark that zips from your finger to the doorknob after you have shuffled across a deep-pile rug carries only about 10^{-6} coulombs of charge; a bolt of lightning has only about 20 coulombs of charge. The charge on one electron is 1.6×10^{-19} coulombs or, conversely, it takes 6.25×10^{18} electrons to make one coulomb of charge.

Electric Current

The reason for choosing such a large unit becomes clearer when we talk of electric current — the transport of electric charge. It is easiest to define current in the case of electrons moving through a wire, as in Figure A5-1. The current, normally designated i, is the amount of charge passing through the cross-section A in one second. The common unit of current, the ampere (often shortened to amp), is one coulomb per second. Therefore, one ampere of current can consist of 6.25×10^{18} electrons passing through A in one second.

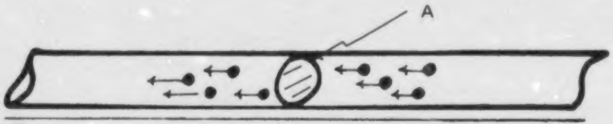
Voltage

Most people know that electric circuits in house wiring are labeled "110 volts." The volt is a unit of "potential difference," a term closely related to potential energy. We will define it by analogy to the gravitational case.

The potential energy of a mass m, lifted a distance h above the earth's surface is increased by mgh. This increase depends, obviously, on the mass m as will the work that produces that change. We can, however, define a quantity, potential difference, which is independent of m by dividing mgh by m. This gravitational potential difference gh describes the work per unit mass required to raise a mass a distance h.

In a similar manner, we can speak of a potential difference which is associated with electric charges and forces. In order to move apart two charges of opposite polarity (+ and −), which attract each other, or move together two charges of similar polarity (++, or −−), which repel each other, work must be performed on them. In doing this work we increase their potential energy. As in the gravitational case, we can define a potential difference as the increase (or decrease) in electric potential energy *per unit charge* or, equivalently, as the work per unit charge required to move charges. Electrical potential difference will, therefore, have the units of joules per coulomb. This combination of units has been given the name volt (after the Italian

FIGURE A5-1
Electron Flow in a Wire



physicist Alessandro Volta, who invented the first battery) and is defined as

1 volt = 1 joule of work per 1 coulomb of charge

To say that a potential difference exists between two points in an electric circuit, is to say that charge at one point will have a greater potential energy than at the other. If left free to move, charge will "roll down the potential hill": + charge travels from + to − potential and − charge in the reverse direction.

If you have a "12-volt" battery, this means that a positive charge at the positive terminal is at a higher potential energy than it would be at the negative terminal. That charge will "fall" in going from the + to the − terminal, performing 12 joules of work for each coulomb of charge that travels around the connecting circuit. This work comes at the expense of the chemical energy of the battery materials.

Electric Current In Wires

Given these definitions, we can discuss the nature of electric current within materials. The most important medium in which charged particles move, from our point of view, is metal — the copper and aluminum wires that carry electric current. In metals, atoms are bound together in a regular and repeating structure called a "lattice" in such a way that their outermost electrons are essentially "free"; the electrons are bound to the material but not to any particular atom. If an electric force is applied to the material, these free electrons can move from atom to atom within the lattice.

It is the "free electrons" which constitute the current in a wire. We visualize these electrons moving in the following way. A copper wire is used to connect the terminals of a battery. For the electron, the + terminal is a low potential, it is "downhill." Electrons at that end of the wire move on to the + terminal leaving that region of the wire positively charged. Free electrons from the region next to this one move in to fill the vacancy and leave their own vacancy behind them. In this manner the electrons in the metal are all set in motion toward the + terminal.

It is obvious that the circuit must be completed somehow. If the electrons just piled up on the + terminal, they would soon be numerous enough to repel any other electrons which tried to leave the wire and the current would cease to flow. It is the job of the battery to "lift" these electrons from the + terminal up to the − terminal where they can enter the wire at the other end.

When a piece of wire is connected between battery terminals, there is a potential difference set up immediately throughout its length. Said another way, each free electron in the wire feels a force that causes it to begin to move. This force field is set up very rapidly; essentially with the speed of light. When you switch on a light, electrons all along the circuit begin to move, current begins to flow, and the light comes on immediately, even though it will take a long time for an electron from the switch region to finally reach the light itself, if it ever does.

D.C. and A.C. Voltages

As we have already shown, the minimal components of an electric circuit are wires to provide and carry the electrons of the current, and a source of potential difference, which causes the electrons to move. We have so far considered only a constant potential difference such as is provided by a battery. A voltage (as we shall begin to designate potential difference) of the type put out by a battery is called D.C. (for direct current) voltage. Such a voltage plotted against time maintains a constant value and direction (that is, the positive terminal remains the positive terminal and the voltage remains 12 volts or 6 volts or whatever).

D.C. voltages have certain important applications: in automobile electric systems, in flashlights, and in electroplating, for example. From the point of view of total electric use, however, the more important type is A.C. (for alternating current) voltage. As is suggested by the name, an A.C. voltage changes in both magnitude and direction — the polarity of the output, + or −, regularly changes as does its numerical value. We will later describe how generators (or alternators, as they are called) produce such a voltage.

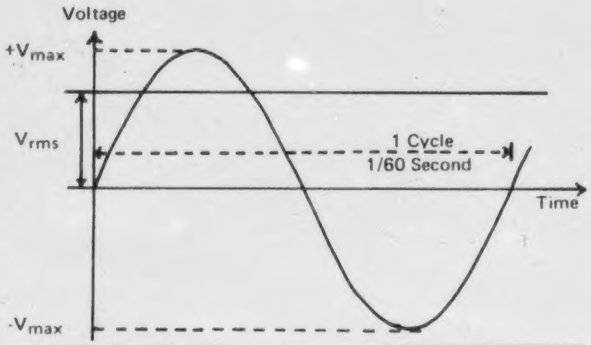
An A.C. voltage has the form, as a function of time, of

$$V = V_{max} \sin \omega t$$

which is shown in Figure A5-2.

The parameter ω determines how many times a second an A.C. voltage changes from + to −. In the United States system, A.C. voltages "cycle" 60 times a second, that is, ω is 60 cycles per second (nowadays called 60 *hertz*) and the polarity is reversed 120 times per second. As we can see from Figure A5-2, it is no longer possible to talk of "the voltage" (or "the current") in the A.C. case, as both these quantities vary with time. What is usually specified is the "rms"* value, which is about .7 times the

FIGURE A5-2
A.C. Voltage



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*"rms" means root mean square, the square root of the average of the voltage squared. For a sinusoidal voltage as shown above, the rms value is $\sqrt{2}/2$ times the maximum.

maximum value. Thus for 110-volt house current, since 110 volts is the rms value, the maximum value is 156 volts.

Resistance

We have identified electric current in wires with the movement of free electrons. When you try to move a charged particle — electron, proton, or ion — through any medium — gas, liquid, or solid — the motion will be resisted. There are, after all, other atoms about and their electrons will be attracted or repelled by the moving charge. They will take up some of its energy just as a moving billiard ball loses energy by collision with other billiard balls. This lost energy contributes to the motion of the atoms of the transmitting medium and, therefore, heats it up.

The motion of the free electrons through the metal is, thus, very erratic. In the first place, the electrons vibrate randomly at relatively high speeds due to the temperature. The applied voltage gives them a small component of motion in the direction along the wire. Thus, the electrons are bouncing wildly about but are drifting on the average in the direction of the electric field. In the metals used for wire, this drift speed depends only on the voltage applied. For this important class of conductors, the current i is proportional to the applied voltage V:

$$i \propto V$$

We can write this as an equation,

$$i = \frac{V}{R} \qquad \text{Eq. A5-1}$$

where R is a constant that takes into account the resistance to motion just described. It depends on the cross-sectional area of the wire and on its length. R is called the "resistance" of the conductor. As the resistance increases, the current decreases and vice versa.

The common unit of resistance is the *ohm* (named for yet another pioneer in electricity, a German high school teacher, Georg Simon Ohm, whose experiments led to Equation A5-1). If V in Equation A5-1 is one volt and i is one ampere, then R is one ohm.

It is this resistance that accounts for much of the loss of electric energy in moving it from place to place. Those electric devices whose purpose is to convert electric energy to heat energy — space and water heaters, toasters, irons, for instance — depend upon high-resistance wires for the conversion. This conversion of electric energy to heat energy can be 100 percent efficient.

The discussion we have just given for resistance holds true whether the applied voltage is A.C. or D.C. The electrons are light enough to respond easily to the change in propelling force produced by an alternating voltage. Thus, the current in a resistive circuit has the same form and the same time relation (it peaks when the voltage peaks) as the A.C. voltage of Figure A5-2.

Electric Power

The final addition to the basic vocabulary of electricity is electric power. Power is work per unit time. Since potential difference —voltage — is work per unit charge — and current is charge flow — charge per unit time — power is dimensionally the product of volts times current.

$$\text{Power} = \text{voltage} \times \text{current} = \frac{\text{work}}{\cancel{\text{charge}}} \times \frac{\cancel{\text{charge}}}{\text{time}} = \frac{\text{work}}{\text{time}}$$

Symbolically:

$$P = iV \qquad \text{Eq. A5-2}$$

Equation A5-2 is exact for D.C. voltages and currents. If A.C. voltages and currents are being considered it can be more complicated, since the voltage and current may not peak together (may be "out of phase," in the jargon). If the electric circuit is purely resistive, however, Equation A5-2 holds for A.C. also.

The unit of electric power is

$$P = \text{volts} \times \text{amps}$$

$$= \frac{\text{joules}}{\cancel{\text{coulombs}}} \times \frac{\cancel{\text{coulombs}}}{\text{second}} = \frac{\text{joules}}{\text{second}}$$

One joule per second is the "watt" we discussed earlier. One watt of power is, therefore, present when one amp of current flows across a potential difference of one volt.

We can also combine Equation A5-2 with Equation A5-1 and learn an important fact about electric power transmission. If we want to deliver a certain amount of power through a transmission line, then, since $P = iV$, we have a choice. We can deliver the power at high current and low voltage or the same amount of power at high voltage and low current: the product determines the power. To force a current i against the resistance R of the transmission line requires a potential difference $V_R = iR$. Thus, an amount of electric power, iV_R, is used up just in transmitting the current i through the line; it is "lost" as heat. This lost power P_e, depends only on the current, that is:

$$P_e = i \times V_R = i \times iR$$

or

$$P_e = i^2R \qquad \text{Eq. A5-3}$$

It increases, in fact, as the square of the current. It is less wasteful, therefore, to ship electric power at high voltage and low current. We will examine this further in our discussion of the transmission of electricity.

The Commercial Generation of Electric Power

The three major steps in the journey of electric power are generation, transmission, and distribution. Each step has its own characteristic problems and makes its own contribution to the national energy-environment problem. The complexity of the power industry is well symbolized by Figure A5-3, which shows all the major steps from fuel delivery to end uses of electricity in a city. The generation of electricity begins with a natural energy source such as gas, oil, or coal. The fuel might then go through special processing before it is sent into the furnace where it is burned to produce steam, which in turn powers the inevitable (and not very efficient) heat engine — the steam turbine. The conversion sequence is chemical energy to thermal energy to mechanical energy. At the end of the production line, the electric generator makes the final conversion to electric energy.

Generators

A simple system which illustrates the principle of electric power generation is shown in Figure A5-4. A "U"-shaped piece of copper wire with a cross piece that can slide on it is placed in a magnetic field. The magnetic field (indicated by the +s on the figure) is perpendicular to the plane of the paper. It could be formed by a north pole of a magnet above the paper and a south pole below the paper.

As we have mentioned before, in a piece of metal, such as copper, the atoms align themselves so that there are loosely-bound electrons, which we called free electrons. If the sliding cross piece is moved from position a to b, these electrons will be physically moved in the magnetic field.

Charges which move in a magnetic field are acted upon by a magnetic force. This is a strange force in comparison to the electric and gravitational forces*. It depends on the velocity of the charge — if the charge is not moving, there is no magnetic force. Its direction of push or pull is strange also. It does not act along either the direction of magnetic field or the direction of motion of the charge, but is perpendicular to both of these. Thus, in Figure A5-4, where the magnetic field is pointed like an arrow into the plane of the paper and the motion of the wire moves the charge to the left in the plane of the paper, the magnetic force points from the bottom of the figure to the top. In other words, as the wire is moved to the left, free electrons are forced to move upward in the wire by the magnetic force.

If it were not for the rest of the circuit, the electrons would pile up at the end of the wire. The remaining circuit allows them to flow as a current *i*, shown by the arrows in the figure. The situation is almost the same as if the top of the slider wire was the positive terminal of a battery and the bottom the negative terminal; the U-shaped loop would be the circuit inside the battery. In other words, there exists a potential difference, a voltage, between the top and bottom of the slider.

This is the basic generator principle. A conducting wire is moved in a magnetic field, a force operates on the free electrons causing them to move and, if the system is properly constructed, a current can be caused to flow across a potential difference and electric power

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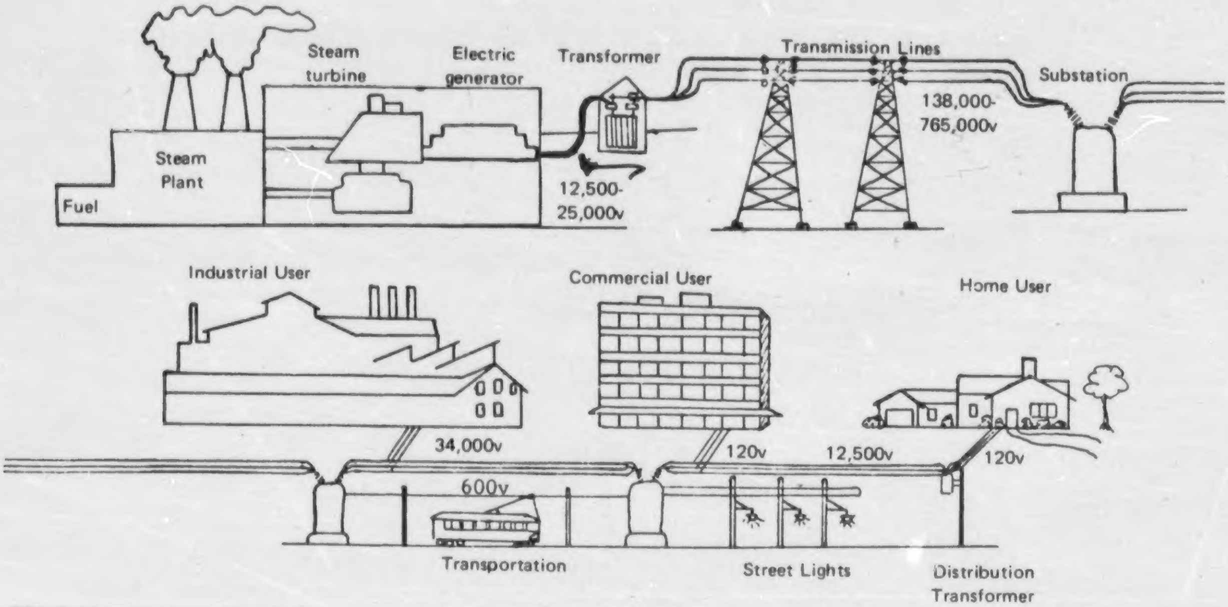
*The magnetic force, however, is not a fourth basic force but, as can be shown using Einstein's relativity relations, is derived from the electric force.

FIGURE A5-3
Generation, Transmission, and Distribution of Electricity



becomes available. We will come back to the question of "properly constructed" later. Let us examine this magic electric power more closely.

We seem to have gotten something for nothing. By sliding a conductor through a magnetic field we created energy. We know, however, that we did not create energy but converted it from one form to another. We had to do work to create the potential difference in the wire. How did this work come about? Let us look again at Figure A5-4.

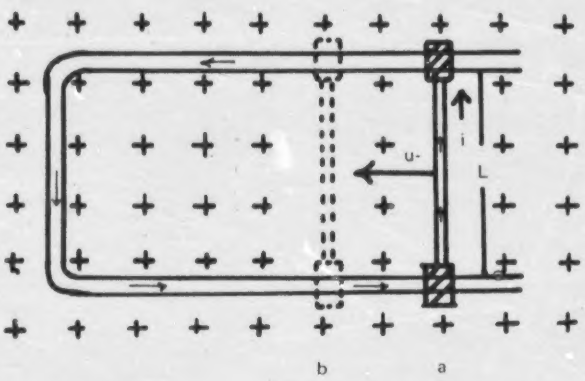
Moving the conductor to the left in the magnetic field causes the current *i* to flow as shown. But a current is made up of moving charges. These charges are now moving up (in the drawing) and they also feel a magnetic force — this one is perpendicular to the direction of current flow and to the magnetic field. If we work out the direction of this force, it *opposes v*. We must, therefore, push against it to keep the conductor moving and, thus, do the work that is converted to electric energy.

The simple system of Figure A5-4 is not of much use as a practical generator. We would get tired pushing the slide wire back and forth. It is much more practical to turn a loop in a magnetic field, as we show in Figure A5-5. Rotary motion is easy to come by, turbines or engines produce it.

To see how we can generate a potential difference by turning a loop we must use a general law discovered 100 years ago by the English physicist, Michael Faraday.

In the example of Figure A5-4, we described the generation of a potential difference in terms of forces. It can be described equivalently in terms of a "magnetic flux." We can think of this magnetic flux, which we will symbolize by the Greek *phi*, Φ, as being the amount of magnetic field in the area *A* surrounded by the "U" and the slide wire. Figuratively, it could be thought of as the number of +s (arrows seen from the rear) in the enclosed area. Faraday showed that a potential difference is generated whenever the magnetic flux Φ changes.

FIGURE A5-4
Generation of an Electric Current by Moving a Wire in a Magnetic Field



+'s indicate presence of magnetic field. North pole is above paper and south pole is below paper

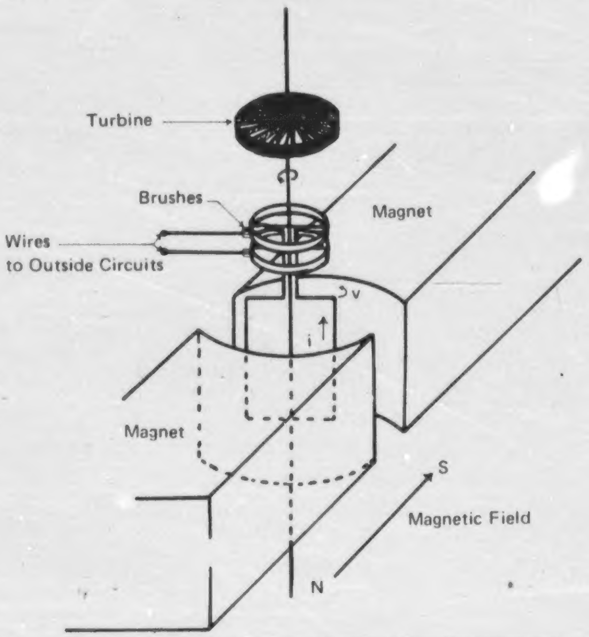
In Figure A5-4 we change Φ by changing the area, making it smaller. Φ will change, however, when the loop of Figure A5-5 rotates in the field, for the area available to the +s becomes smaller as the plane of the coil goes from a position perpendicular to the field to a position lined up with the field. In this latter position, the flux is zero since *no* arrows can go through the loop. You can perhaps visualize this if you think of one pole of the magnet as a flashlight and the other as your eye. As the loop rotates, the area enclosed by the shadow of the loop is first a maximum, then after a 90°-turn it is zero, then another 90°-turn brings another maximum, and then after 270°, another minimum.

Since the area is varying, the magnetic flux is varying, inducing (according to the physical law developed by Faraday) a potential difference, and a current will flow through the complete circuit.

It should be clear that the voltage generated by a rotating loop will alternate. It will be a maximum in one direction when the loop is perpendicular to the magnetic field, go to zero after a 90°-turn and then build back up to a maximum in the other direction after 180°, go to zero again and so on. From simple geometry, in fact, you can show that the voltage will have on average the form, sin ωt, described previously.

The rest of the generator is fairly straightforward. To connect the wire loop to an outside electric circuit for use, the ends of the wires are connected to two continuous rings which also rotate. Wire brushes at the end of connecting wires can be used to rub against the rings as they rotate, enabling the current to flow in an exterior circuit.

FIGURE A5-5
Model of an Electric Generator



These then are the basic features of electric generators. The actual generators in use today are much more complicated devices than the one shown, but they have the same features — a series of coils that turn in a magnetic field and sliding contacts (brushes) to bring out the generated current.

The generator is, of course, only part of the system. It requires something to turn it. There are presently only two important sources of mechanical energy to turn generators — the heat engines discussed in Appendix 4 and "hydropower" from the kinetic energy of "falling" water. The heat engines dominate the picture, providing motive power for 85 percent of the generated electricity, with hydropower providing the remaining 15 percent. Of the various heat engines, the most important is the steam turbine, which generates 76 percent of the electricity. The efficiency of this conversion — thermal to mechanical to electrical — is inexorably limited by the efficiency limits on heat engines we have discussed in Chapter 3 of Volume II: electric power has to come through the "thermal" bottleneck. The emergence of nuclear-fueled generating plants will *not* bypass this bottleneck for, as we shall discuss in Appendix 6, nuclear energy is also converted to thermal energy. The electrical conversion in these plants will also be made by a steam turbine — generator set.

It should be emphasized that the generator itself neither stores nor produces energy. What it accomplishes, and with efficiencies close to 100 percent, is the conversion of kinetic mechanical energy into kinetic electric energy. Sitting still it is just a lump of metal.

Transmission and Distribution of Electric Power

Electricity is kinetic energy; it must move out from the generating plant, be transmitted to the consuming area, and then be distributed to individual users. Electricity is produced at 12,500 to 25,000 volts, depending on the generator. It is not transmitted at these relatively low voltages, however, for as we discussed earlier, losses due to the resistance in the transmission lines are proportional to the current squared (i^2). Electric power is thus transmitted at the highest voltages (and lowest currents) possible, as high as 765,000 volts on some transmission lines and at greater than 200,000 volts in most places.

Electric power is transmitted across the country in the familiar "high-tension lines." There are now about 300,000 miles of these lines in service across the country, and 500,000 miles are anticipated by 1990.

Transformers

The voltage has to be increased for transmission and then decreased (to 110 volts) for use. Fortunately, there is a device which accomplishes this called, appropriately enough, a "transformer."

Figure A5-6 is a schematic drawing of a simple transformer. The important components are the two sets of coils wound around opposite sides of a continuous "core" of iron. Suppose we first consider a low voltage — say 100 volts — applied to the side with the single coil, the "primary" winding. Current in a coil wrapped around iron sets up a magnetic field in the iron. (This is how electromagnets are built.) The magnetic field goes all around the iron core (as shown by the B lines) and, specifically, it passes through the many coils (we have drawn 10) on the other side. This is the "secondary" winding.

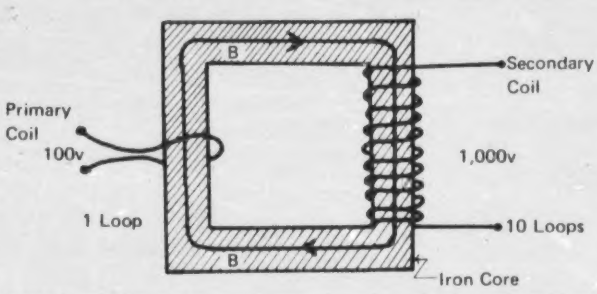
If the 100 volts which are applied from the left are A.C., the magnetic field in the iron varies in the same way. It starts at a maximum, goes to zero, reverses its direction, and goes to a maximum in the new direction. What will be the effect of this changing magnetic field on the "secondary" coils?

The changing magnetic field that passes through the many coils of the secondary winding produces a changing magnetic flux Φ through these coils. As a result, a potential difference is induced in *each* of the coils of the winding according to Faraday's law discussed earlier. Whereas the changing flux in the generator model of Figure A5-4 was due to changes in the area perpendicular to the magnetic field enclosed by the wire loop, here the area of the loop is constant but the strength of the magnetic field changes.

The origin of the changing flux in the secondary coil is the changing flux in the primary coil produced by the applied 100 volts A.C. Since the changing flux in *each* secondary coil must be the same, the induced potential difference, or voltage, in *each* turn must be equal to 100. The coils are connected, and, therefore, these potential differences (voltages) add on and the total voltage in the secondary coil is 10 times the primary voltage. The step-up in voltage, therefore, depends on the ratio of the number of coils in the secondary to the number in the primary. It should be obvious that to step voltage down, one merely works the transformer backward.

Since energy is conserved (or nearly so, since the heat losses are small), the input and output power (energy per unit time) must be the same. If the voltage changes, something else must change. The current is the only candidate. Thus, on the left we have low voltage, high current and on the right we have high voltage, low current.

FIGURE A5-6
Model of a Transformer



Distribution

Returning to Figure A5-3, we see that after the electric power arrives at the many transmission substations the voltage is reduced to 12,500 volts by transformers and sent out over the distribution system. Two paths are available: the wooden poles, with their insulator-dotted cross-arms, or underground cables. The distribution system is the individualized performer. It must get power to where it is needed and provide it at the right voltage and quantity to the ultimate consumer. It accomplishes this through additional voltage transformation at the point of use.

A large steel company, for example, takes its power directly from the high-voltage transmission lines and the utility company's transformer steps the voltage down to 34,000 volts. Huge amounts of power at this voltage will be used to heat electric arc furnaces for the production of steel.

For the residential consumer and the commercial customer, the voltage is stepped-down to either 120 or 240 volts (we usually refer to it as 110 and 220 volts — the actual values differ a bit from company to company). In this form it is ready for our use to power lights, appliances, and other home electric conveniences.

Electric power production and consumption is in many ways symbolic of the crises in energy and the environment. It has been, for the past two decades, the most rapidly increasing form of energy and its ready availability is the definition of "modern." In its production, from coal or oil or uranium, however, we threaten our environment in myriad ways. Description and discussion of these threads of the story of electric power occur throughout the two Source Book volumes.

APPENDIX 6
Energy from the Nucleus

Energy from the Nucleus

In this Appendix, we will explain why there is energy stored in the nucleus, and how we can get it out. We will confine ourselves to the minimal nuclear physics needed to understand nuclear reactors and their byproducts.

Nuclear Structure

Terminology

The basic chemical structure is the atom. At its center is a small, dense core called the nucleus; about 10^{-12} centimeters in diameter — 1/10,000 the size of an atom — like a jelly bean in the center of the Astrodome. (If a jelly bean were as dense as the nucleus, however, it would weigh about 100 million tons.)

The nucleus is composed of electrically charged protons and uncharged neutrons. Protons have the same amount of charge as electrons (it is of opposite sign) and are about 2,000 times heavier. Neutrons are similar in mass but slightly heavier than protons.

The number of protons in a nucleus is equal to the number of electrons in the shell of the atom. Thus, atoms are uncharged. Since the atom's chemical properties are determined by the number of electrons, a nucleus can have the same number of protons but different numbers of neutrons and still be the same element. Nuclear species with identical proton numbers but with different neutron numbers are called isotopes. Hydrogen, for example, has a rare, heavier isotope, called deuterium, that has one neutron in its nucleus in addition to its one proton. It also has a radioactive isotope, tritium, with two neutrons plus a proton in the nucleus. We identify the isotopes by an initial which designates the atomic element and give, as a superscript, the number of particles — the number of neutrons, plus protons — in the nucleus. For example, H^1, H^2, H^3 designate hydrogen, deuterium, and tritium, respectively.

While we are introducing terminology, we will also define the energy unit most commonly used in nuclear physics — the MeV, which stands for million electron-volts. It was found in the study of atomic structure that atoms could be taken apart by bombarding them with electrons accelerated by a potential difference (see Appendix 5) of a few volts. Since charge times potential difference is energy, the natural unit of energy in atomic physics became the eV (electron-volt). The natural unit of nuclear energy is a million times larger, MeV instead of eV, since the nuclear force is so much stronger than the electrical force.

Compared to one Calorie, however, one MeV is a small quantity. There are 2.6×10^{16} MeV in each Calorie or, equivalently, 1 MeV = 3.83×10^{-17} Calories. This may seem a paradox. The natural unit of nuclear physics, which is associated with the tremendous energies released in atomic bomb blasts, is so much smaller than the unit associated with the energy content of the foods we eat. The answer, of course, lies in the fact that when we speak of food Calories, we are describing the energy in an average serving — be it a cup, a pint, or three tablespoons — and *not* the energy resulting from *one atom* interacting with *another atom*. For example, in the very basic reaction of the burning of carbon, about 2 Calories are released for each gram of CO_2 (carbon dioxide). However, in 1 gram of CO_2 there are roughly 1.3×10^{22} molecules. Thus only 1.5×10^{-23} Calories are released in the formation of one molecule of CO_2 through "burning" carbon, a number of Calories equal to about 4 eV.

This should suggest to you that the energies we can obtain in nuclear reactors from grams of materials are going to be much larger than the chemical energies we get from burning common fuels. How these energies are obtained is the next part of the story.

Energy, Stability, and Nuclear Structure

In the nucleus of the atom, the neutrons and protons are in constant motion. They are held there by the very strong nuclear force. Like most systems in nature, neutrons and protons like to arrange themselves in the nucleus in a stable structure — in a position of minimum potential energy. Like loose rocks on a hillside, they will seek positions which cannot easily be disturbed — they "roll into the valley." Also, because nuclei have a complex structure, some are more eager to accept neutrons or protons (more loose rocks) than others. If their structure is unstable, they are *radioactive*. They undergo a "rockslide," a nuclear transformation, to change their internal structure and gain stability.

It is relatively easy to distinguish stable nuclei — they are the ones that are most plentiful in our planet's soil and rocks. Unstable, or radioactive, elements or isotopes have long ago transformed, or are transforming, themselves into stable ones.

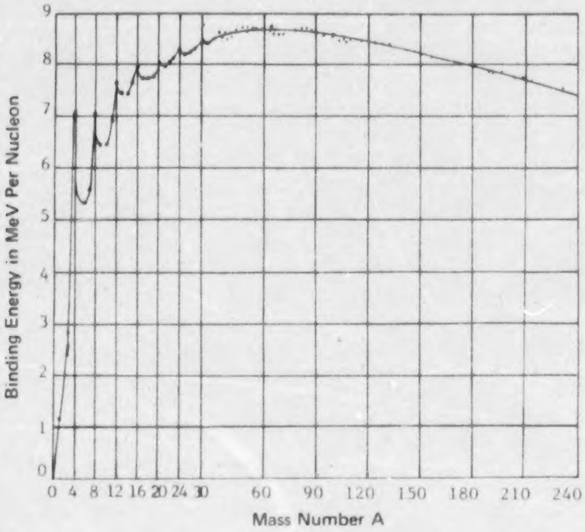
We can learn something about the conditions of nuclear stability by looking at the characteristics of all stable nuclei. What we find is that the light nuclei, those with atomic weights (the sum of the number of neutrons and protons) less than 40, seem to have equal numbers of neutrons and protons. As the atomic weight increases, stable nuclei prefer to have more neutrons than protons. There are several reasons for this, but the most important one is easily understood: the electrical repulsion hinders the addition of more protons, but there is no repulsion for the uncharged neutrons. As the number of particles gets very large (greater than about 210), however, even these large nuclei are no longer stable. It is in this region that we find the fissionable nuclei, U^{235}, U^{238}, and Th^{232}.

As with rocks which have fallen into a well, it takes energy to remove neutrons and protons from a nucleus. The characteristics of stable nuclei indicate that it takes differing amounts of energy to remove particles from different nuclei. For very heavy nuclei, less energy is needed. This variation is shown in Figure A6-1, which displays the "average binding energy" per nuclear particle in the nucleus. The *binding energy* (B.E.) is the total energy necessary to take a nucleus apart, one nucleon at a time. A, the number of nucleons, equals the sum of the number of neutrons plus protons. What we see is that B.E. per A fluctuates for the very light nuclei but is always less than 8 MeV. It then climbs to a broad maximum of a little more than 8 MeV from $A = 50$ to $A = 100$ and then falls slowly as A gets larger. The reasons that B.E. per A is less than 8 MeV in the region of the light nuclei are too complex to discuss here, but the main contribution to the large nuclei fall-off is the electrical repulsion of protons, which we have mentioned.

The curve in Figure A6-1 tells us, in effect, the most stable configuration of a given number of nuclear particles. For example, if we have four particles ($A = 4$), we find from the curve that the total binding energy of a mass 4 nucleus would be: 1 nucleus × 4 nucleons per nucleus × 7 MeV per nucleon = 28 MeV. In contrast, two nuclei of mass 2 would only have a binding energy of: 2 nuclei × 2 nucleons per nucleus × 1.1 MeV per nucleon = 4.4 MeV. Thus, the nuclear "well" is deeper for forming one nucleus out of four nucleons as compared to forming two nuclei of two nucleons each; the mass 4 nucleus, He^4, is more stable than two mass 2 nuclei, H^2.

The two ways in which nuclear reactors can provide energy are summed up in Figure A6-1. One way is to take the two light nuclei we mentioned, H^2, and put them together to make He^4. Since the binding energy is not only a measure of the stability of a nucleus but also of the energy given off in its formation, excess energy equivalent to 28 MeV minus 4.4 MeV = 24 MeV would be given off in the reaction. In other words, the potential well the H^2 fall into when they combine to form He^4 is a little deeper than the one they were in separately and so energy is released. This is the *fusion* reaction whose potential for practical realization we discuss in Chapter 7 of Volume II.

FIGURE A6-1
Binding Energy Per Nucleon



Note: horizontal scale changes at A = 30.

Energy can also be gained by working from the other end. If we take a heavy nucleus, like U^{235}, and split it into two nuclei, like Sr^{98} and Xe^{137} (strontium and xenon), we see that B.E. per A is greater for either of the two than it was for U^{235}. B.E. per A is approximately 7.6 MeV per nucleon for U^{235}, whereas for Sr^{98} and Xe^{137}, it is roughly 8.5 MeV per nucleon. The difference between one nucleus of 235 particles and two nuclei of approximately half the number is about 1 MeV per nucleon. The *total* energy released by the 235 nucleons involved, therefore, is around 200 MeV. The U^{235} nucleus is energetically, so to speak, up on the side of the hill; it can fall down and split into two nuclei and be in a more stable situation.

There is another way to say the same thing. Einstein showed as one of the consequences of his theory of relativity that mass and energy are two forms of the same thing and related by the famous equation $E = Mc^2$ (where E is the energy, M the mass and c, the conversion constant, is the velocity of light).* What we have just said about the difference in binding energy could have been said in the following equivalent way: If (in the fusion example) we measure the mass of the two deuterium nuclei, H^2, and the mass of the helium nucleus, He^4, we find that the He^4 has a little bit less mass than the sum of the masses of the two H^2's. It is this missing mass that is converted into energy. Similarly, in the fission example, the two nuclei, Sr^{98} and Xe^{137} have less mass than did the original U^{235} — the difference has been converted to energy.

The 200 MeV released per nucleus is not much energy. As we pointed out before, a MeV is small compared to a Calorie. However, in a kilogram of uranium, there are $2.6 = 10^{24}$ nuclei. Thus, in theory, the total energy available from the fissioning of all the nuclei in a kilogram of uranium is $E = 2.6 \times 10^{24}$ nuclei × 200 MeV × 3.83×10^{-17} Calories per MeV, which is 2×10^{10} Calories, or 20 B Calories, the energy equivalent of 3,000 tons of coal. Let's look at this fission reaction more closely.

Fissioning for Energy

We have shown how very heavy nuclei are energetically ripe for fissioning. They can be viewed as liquid droplets, which are not spherical but football-shaped, with the protons concentrated at the ends. Since the nuclear force is very strong, the droplet remains together. However, anything that stretches the nucleus farther will encourage the electrical repulsion between the opposite ends of the football and split the nucleus. It is all set to fly apart, all it needs is a trigger.

Neutrons provide the trigger. This uncharged particle is an ideal projectile; the strong electrical force of the highly charged nucleus can't keep it away. When the neutron hits the nucleus, it not only gives up its own kinetic energy but it drops into the energy well of the nucleus and its binding energy is released.

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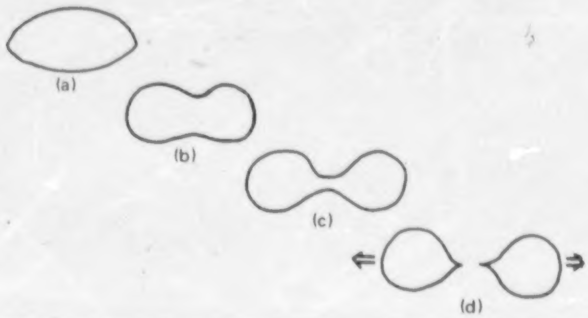
*If M is expressed in kilograms and c is taken to be 3×10^8 meters per second, then the energy unit of E will be the joule.

The nucleus which captured the neutron now is unstable, it must rid itself of the extra energy. Although there are many different ways by which this can be accomplished, we will consider only the one that leads to fission. That mode is illustrated in Figure A6-2. These heavy nuclei are elongated, as in Figure A6-2a, and the nuclear forces are weak at the ends. If they go into a certain kind of vibration, they may begin to "neck down," as in Figure A6-2b. When this happens the electrical repulsion between the protons begins to dominate, the neck stretches, and then breaks, as in Figures A6-2c and A6-2d. The two pieces fly apart carrying the 200 MeV of energy. This kinetic energy is quickly converted to heat energy by collisions within the nuclear fuel material.

Any heavy nucleus can be caused to fission if it is hit with a sufficiently energetic neutron, say one of a few MeV. The nuclei used as bomb and reactor fuel, however, have a very special structural feature: their well for additional neutrons is deep; the neutrons release 6 MeV or so of binding energy when absorbed by the nuclei. The neutron does not need to bring much kinetic energy of its own to such a nucleus, even a very low-energy neutron (a "slow," or "thermal," neutron) wandering by can be captured, and with the released binding energy, start the fission-producing vibrations. Furthermore, a slow neutron stays in the vicinity of a nucleus longer and is, therefore, more easily captured than a fast (energetic) one.

There is only one naturally occurring nucleus, the rare isotope of uranium — U^{235} — which can capture these slow neutrons and undergo fission. Two other nuclei, U^{233} and Pu^{239}, can be produced in a reactor and will also serve as nuclear fuel. (It is the capacity to produce these fuels that creates most of the interest in the breeder reactor which we will discuss later.) The reactors we presently depend on use U^{235}, which makes up only 0.7 percent (one nucleus out of 140) of natural uranium ore. Luckily, U^{238} is the dominant isotope. It needs a fast neutron to make it fission. If this were not the case, any chunk of uranium ore would blow itself apart, triggered by the "slow" neutrons constantly bombarding earth from cosmic radiation.

FIGURE A6-2
Steps in the Fission Process



Chain Reactions and Their Control

In order to use U^{235} as a fuel, we must first gather enough of it together, then set it off, and, most important of all, control the reaction. A single U^{235} nucleus will capture a neutron, receive the 6 MeV binding energy, go into the vibrations we describe, and, finally, fission. The two pieces, the so-called "fission products," carry off the 200 MeV of kinetic energy.

The 200 MeV from one nucleus is, as we have said, not very much energy. To get usable amounts of energy we have to find some way to make essentially all the 10^{25} or so U^{235} nuclei in a chunk of uranium undergo fission. For this we must rely on the other pieces, the neutrons, which also fly out when the nucleus fissions. These neutrons have a considerable amount of energy, which they quickly lose by collisions with the matter around them. After they are slowed down, they can strike other U^{235} nuclei and cause them to fission. They offer, therefore, the possibility of igniting a "chain reaction" — one nucleus releasing neutrons which cause other nuclei to fission releasing more neutrons, and so on. It is of obvious importance to know how many neutrons are released per fission. If only one, on the average, is released, then the reaction started by a blast of neutrons doesn't grow, but at least continues. With less than one neutron released, it dies out. The explosive release of energy we are looking for needs more than one neutron released per fission. Fortunately, for our need of electric power, the average number of neutrons released in the fission of U^{235} is 2.6. This is more than enough for a chain reaction.

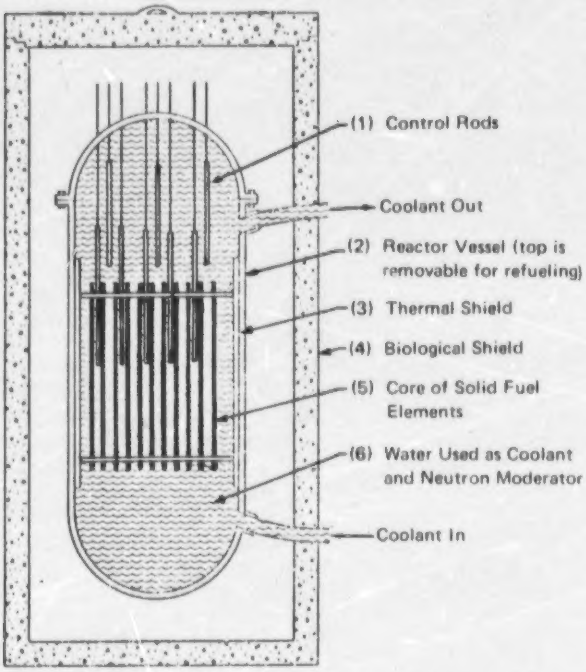
For the chain reaction to proceed, these neutrons must remain available. They must also be slowed down, for as we have mentioned earlier, slow neutrons are much more readily captured by U^{235}. The most effective way to accomplish this is to have the neutron strike something of its own size — a proton, for instance. In such a collision it loses half of its energy, while in striking a much heavier nucleus it will only lose a small fraction of its energy. Thus, water, H_2O, would seem to be a good substance to slow down neutrons — a good "moderator," in reactor terminology. Of course, the U^{238} which is always abundantly present in a nuclear fuel sample, also acts as a moderator, but it takes many more collisions with this heavy nucleus to slow the neutrons. Other commonly used moderators are "heavy water," D_2O, in which the hydrogen is replaced by its chemically identical isotope deuterium (D is the H^2 we have earlier identified) and carbon, C^{12} (usually in the form of graphite). These latter two moderators have the advantage that they do not "capture" neutrons as hydrogen does and thereby take them out of the chain reaction.

The size of the uranium fuel assembly is also of importance to the success of a chain reaction. If it is too small, then neutrons go out through the sides and are lost in that way. The size criterion is embodied in the term "critical mass," which became familiar in discussion of the fission bomb. A certain amount of U^{235} of a given concentration is needed before the chain reaction can occur. When this "critical mass" is assembled, however, the chain reaction begins: a U^{235} nucleus fissions when struck by a slow neutron, the two or more neutrons released in the fission of this first nucleus fly off, are slowed down by collisions with the moderating substance, captured by other U^{235} nuclei and cause them to fission and release more neutrons, and so on. The chain reaction grows and involves the entire fuel element in a few thousandths of a second. Uncontrolled, the critical mass explodes. Roughly, this is how an "atomic bomb" works. The fuel is kept in pieces smaller than the critical mass and then brought together when on target. What is needed for a nuclear reactor is some way to control, slow down, the "chain reaction."

Controlled fission: To control a fission chain reaction, it is necessary to find some way to take enough neutrons out of circulation with each generation of fission events so that the explosive build-up does not occur. In fact we want sometimes to be able to take out so many neutrons that less than one per fission is available, and thereby to shut off the chain reaction.

There are several substances which can capture neutrons; boron is one commonly used. This material is put into a *control rod* which can be pushed into or pulled out of the assembly of fuel rods of the reactor core, as is shown in Figure A6-3. The number that are inserted and the depth to which they are inserted determine the neutron flux and thus the power level at which the reactor operates.

FIGURE A6-3
Nuclear Reactor Core


(1) Control Rods
Coolant Out
(2) Reactor Vessel (top is removable for refueling)
(3) Thermal Shield
(4) Biological Shield
(5) Core of Solid Fuel Elements
(6) Water Used as Coolant and Neutron Moderator
Coolant In

Source: "Nuclear Reactors," USAEC, Division of Technical Education, pg. 3.

Electronic "neutron counters" are used to control the setting of the control rods and, when the neutron count raises to a dangerous level, to "scram" the reactor; that is, to shoot extra control rods into place and shut the reactor off.

In addition to the control rods, it is also possible to stop the chain reaction by adding boron, in the form of boric acid, to the cooling water circulating in the reactor. Most reactors have both of these control and safety techniques available. Some of the control operation is automatic. It must be, for the build up of neutrons is very rapid and succeeding generations are only about 10^{-4} seconds apart. Fortunately, in the conventional "light water" reactors (we'll explain this term in the next section) some neutrons from each generation are delayed by several seconds and thus provide some leeway. One of the worries with the plutonium-fueled reactors, such as the breeder (which we shall discuss later), is that since there are not as many delayed neutrons, the control situation is much more delicate.

Nuclear Power Plants

In the crude picture of a nuclear reaction which we have sketched, there are three main elements: fuel, moderator, and controls. The energy is released by the fuel, the moderator feeds low-energy neutrons back into the fuel to sustain the fission reaction, and the neutron-absorbing controls take the neutrons out of the chain reaction and slow it down or stop it. Let us look now in more detail at reactor structure.

Reactor Construction

The working components of a fission reactor are shown schematically in Figure A6-3. The fuel, usually in the form of a "sintered"* pellet of uranium dioxide, UO_2, is contained in a series of "fuel rods." These rods are about one-half inch in diameter and 12 feet long. The fuel is contained inside a "cladding" of some noncorrosive, light, strong metal such as zirconium.

These fuel rods are then arranged in a bundle of 40 or 50 rods and assembled with the "control rods" to form a fuel assembly. A commercial reactor contains several hundred individual fuel rods. In Niagara Mohawk's Nine Mile Point generating unit, with 625 Mw capacity, there are 532 bundles of 49 rods containing 115 tons of uranium oxide pellets.

The rods are surrounded, in United States reactors, by water, which serves a dual purpose. It acts as a moderator by slowing down the fast neutrons released by fission, and it also serves as a coolant. This latter function is equally important. As we have said, the energy of the fission products is quickly converted to heat energy by collisions with the remaining material in the rod. Thus the fuel rods get very hot and would quickly melt if the circulating water did not continually remove the heat energy. This is also the mechanism by which the energy of the reactor is retrieved.

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*Heated and formed into a ceramic.

Types of Reactors

A fuel core and control rods plus circulating water, as coolant and moderator, are the basic components of an operating nuclear energy conversion device. Also required are ways to get this heated water to a heat engine, convert it to mechanical work, and turn a generator. It is in the accomplishment of this heat transfer that differentiation between various reactor types takes place. In this country, at the present time, all commercial reactors are thermal, or slow, neutron reactors. Light water-moderated, they use enriched uranium as fuel; that is, uranium in which the amount of U^{235} has been enhanced by three to four times its natural abundance. There are two basic types now in use: the boiling water reactors, BWR; and the pressurized water reactors, PWR. Generically these are the light water reactors, LWR.

PWR: The *pressurized water reactor* contains, as the name suggests, water under very high pressure, as high as 2,000 pounds per square inch. There are, in fact, two separate water circulation systems, as is shown in Figure A6-4, and it is the high-pressure system that is in contact with the reactor core. At such high pressures water does not boil at the normal 212°F and, therefore, it remains a liquid at the 600°F it reaches in the reactor core. This heat energy is then transferred through a "heat exchange" to the second circulating system of low pressure water in which it produces steam to drive the steam turbine.

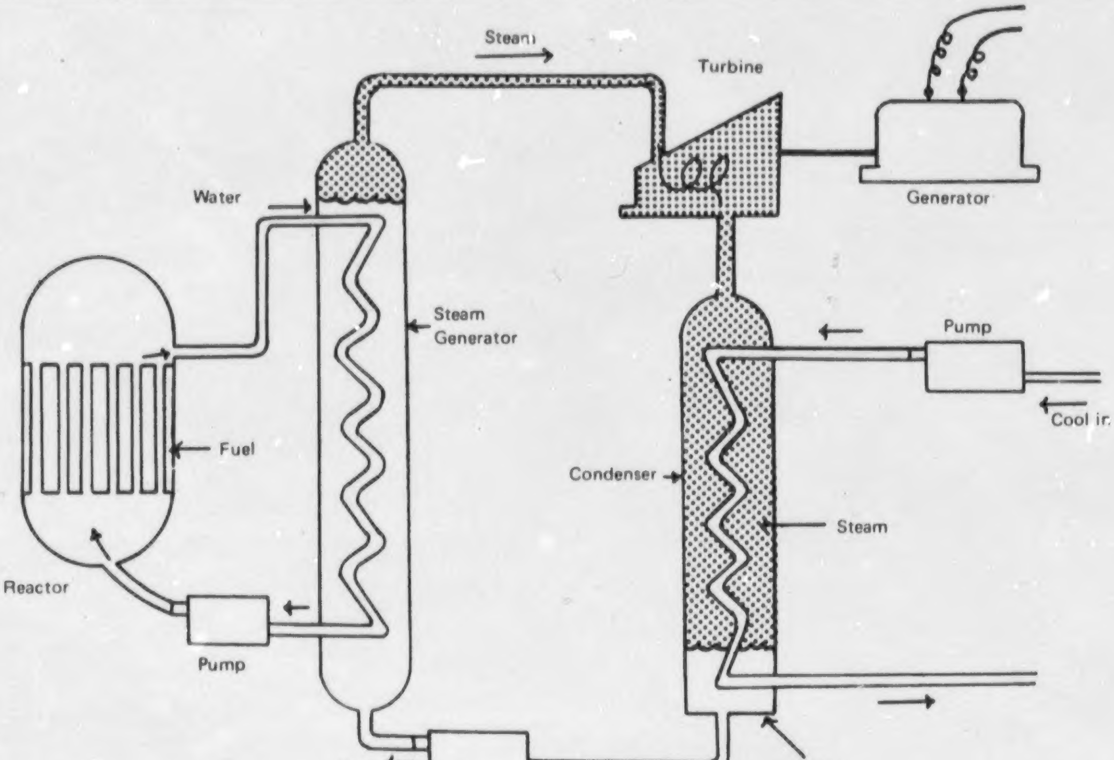
From the turbine on, the operating machinery is basically the same as in a fossil fuel plant. In particular there is still need for a third water circulating system to condense the steam back to water. In contrast to the first two systems, which are essentially closed, this last one is open and connected to a body of water or a cooling tower.

In the PWR it is easier to contain the radioactive materials that inevitably leak through the fuel rod cladding. The first pressurized system is completely separated from the other parts of the system and, in particular, from the turbine.

The PWR reactor was the first one to be put into commercial service, at the Shippingsport, Pennsylvania, plant in 1957. It is also the type used in nuclear submarines.

BWR: The *boiling water reactor* has only one circulating water system in which the water is at lower pressure (about 1,000 pounds per square inch) and is allowed to boil. As is shown in Figure A6-5, the steam generated by this boiling rises to the top of the core region and, after passing through steam separators and dryers, is piped directly to the turbo-generators.

FIGURE A6-4
Pressurized Water Reactor (PWR)



Since the steam comes in contact with the fuel rods in the BWR, this reactor could release radioactive pollutants to the environment. There is always some leakage of fission products from the rods and some water-borne impurities made radioactive by the neutron flux in the core. It is thus important that the steam be tightly contained and not allowed to escape.

The first commercial BWR was installed at Commonwealth Edison's Dresden, Illinois, plant in 1960.

HTGR: There is some interest in a new type of reactor, the *high temperature gas-cooled reactor*. This reactor, while it is a "converter" (like the BWR and PWR) and not a "breeder," does produce new fissionable material. It differs from the light water converters in having graphite as a moderator and helium as a coolant. The helium circulating through the core reaches a temperature of 1,400°F and, through a "heat exchanger" (coils immersed in water), produces steam at 1,000°F. The HTGR thus offers the possibility of a thermal efficiency of 40 percent — comparable to the best fossil fuel plants. Studies are also under way on the feasibility of using the hot helium directly in gas turbines, which would increase their efficiency even more. A problem of the HTGR is that the helium must be forced to circulate rapidly in order to carry the heat away. A power loss is thus extremely serious.

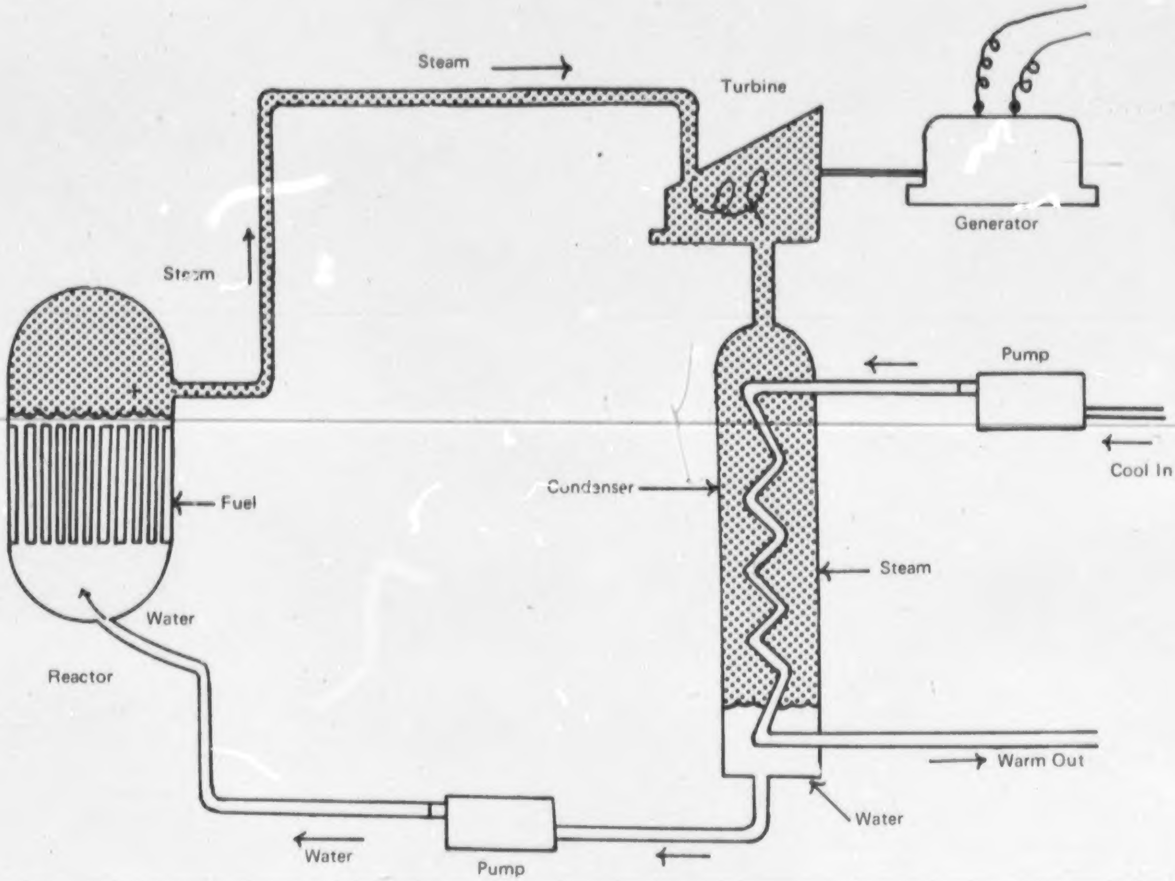
In the HTGR it is possible to add thorium, Th^{232}, to the reactor and create more fuel. The thorium nucleus can capture a slow neutron and be converted to U^{233}, which, like U^{235}, is a good nuclear fuel. This reactor is called an "advanced converter", since it does create some fuel for itself out of the non-fissioning component.

An experimental HTGR of 40 Mw is in operation at the Philadelphia Electric Company's Peach Bottom site, and another of 330 Mw is being constructed at Fort St. Vrain, Colorado. Whether this type will become important in the future depends on the experience with these plants and on the success of the breeder reactors, which they to some extent anticipate.

Breeder Reactors

The reactors we have discussed so far are classified as "converters," their major purpose is to convert the fissionable fuel — almost exclusively U^{235} — into energy. Although the energy these reactors produce, per ton of fuel, is quite impressive when compared with fossil fuel plants — less than 200 tons of uranium per year for a 1,000 Mw reactor as against 2 million tons of

FIGURE A6-5
Boiling Water Reactor (BWR)



coal for a coal-fired plant of the same capacity, there are not many thousands of tons of uranium around. It was natural, from the beginning of the nuclear age, to look for other fissionable fuels.

What is required to make a nucleus fissionable by slow neutrons is a particular structure. It has to have, so to speak, a hole for a neutron to fall into so that the probability of neutron capture will be high and a sufficient amount of energy will be released. U^{235} is the only naturally occurring nucleus which has that structure.

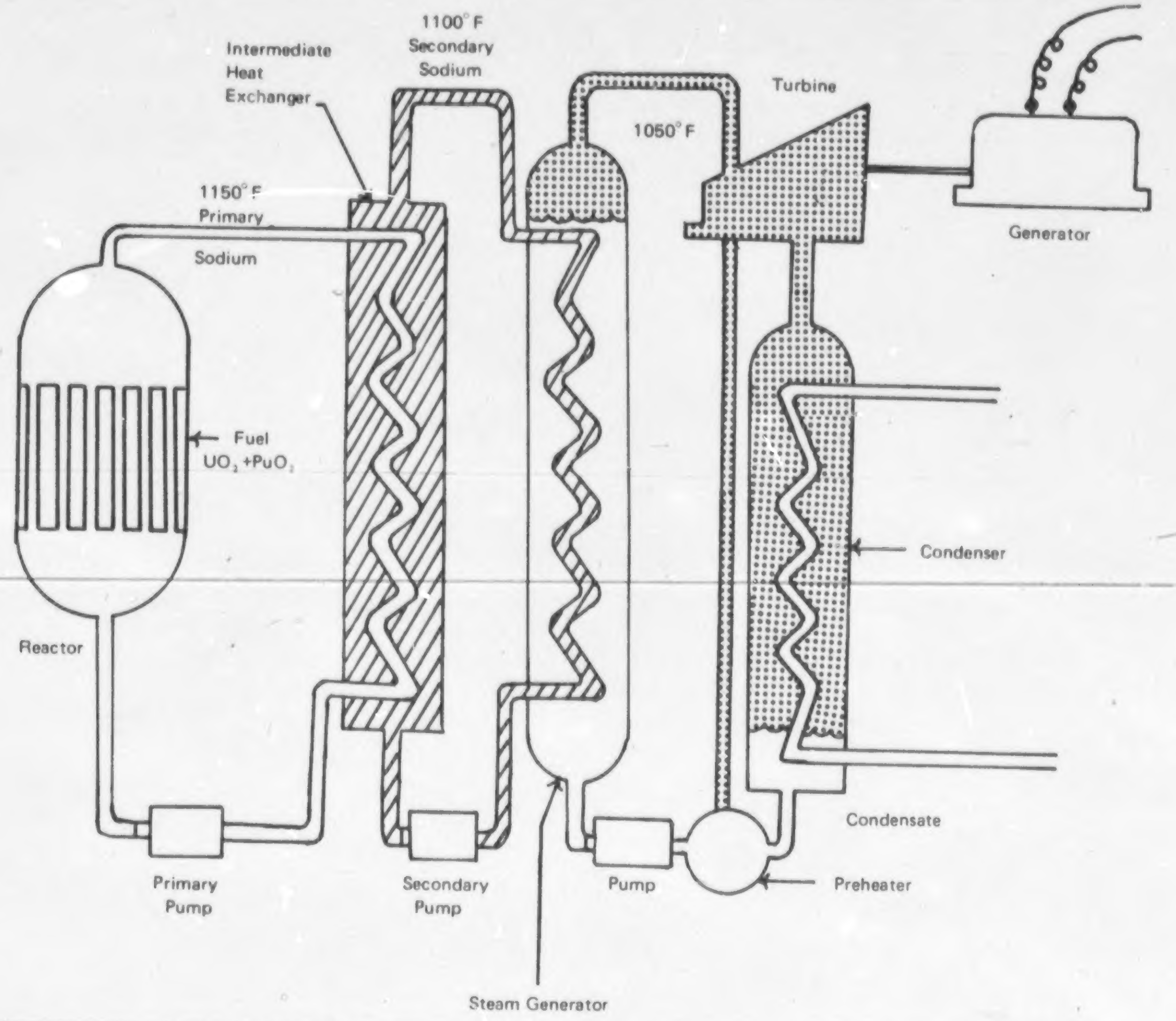
There are two artificial isotopes, U^{233} and Pu^{239}, that can be created in neutron reactions. U^{233} is produced by the neutron bombardment of Th^{232} (thorium). Pu^{239} is produced in the same way from U^{238}. Since thorium is actually a little more plentiful than uranium, and U^{238} has been, so far, considered a waste material, the addition of these two elements promises to greatly extend the supply of fissionable fuels.

In order to "breed" fuel, to produce more fuel by these reactions than is used in the core, there must be more than two neutrons per fission available. One of these sustains the chain reaction and the other is used to convert U^{238} or Th^{232}. The success of a breeder is measured by the breeding ratio, B.R., the ratio of the amount of fissile fuel produced to that used up. A second measure of importance is the "doubling time," the time it will take for a breeder reactor to produce enough fuel to run a second reactor.

There are two types of breeder reactors: the thermal breeder reactor, which uses slow neutrons, and the fast breeder, which uses more energetic neutrons. The thermal breeder works with Th^{232} as fuel and the fast breeder with U^{238}. Most of the present research and development effort is going into the fast breeder.

The LMFBR: In the *liquid metal fast breeder reactor*, (Figure A6-6), unmoderated, "fast" neutrons from the

FIGURE A6-6
Liquid Metal Fast Breeder Reactor (LMFBR)



chain reacting core produce Pu^{239} in a surrounding blanket of U^{238}. In this reactor, the B.R. may be as high as 1.5 and the doubling time 8-10 years. This is of particular significance since it is about the doubling time of electric energy consumption. Thermal breeders are slower; the B.R. is 1.05 and the doubling time 21 years.

Since the neutrons in the LMFBR must be unmoderated, water cannot be used as a coolant. What is needed is a relatively heavy material (to minimize collision energy losses) with good heat transfer properties and a high heat capacity. The current choice is molten sodium.

The LMFBR will have the major components shown in Figure A6-6. The reactor core will be immersed in liquid sodium, which, because of its high boiling point, can be heated to 1,150°F. Since this sodium will be made highly radioactive by neutron bombardment, there will be a secondary sodium coolant loop between the reactor and the steam generator which will produce steam at about 1,000°F, giving an anticipated thermal efficiency of 40 percent.

The core will be surrounded by a "blanket" region composed of bundles of rods fabricated from the uranium left over at the enrichment plant — uranium depleted of U^{235}, almost pure U^{238}. Pu^{239} will be produced, therefore, in the blanket as well as in the fuel rods.

There are many problems posed by using sodium as a coolant. It is opaque, making it difficult for the operator to see into the reactor during refueling and other core maintenance operations. Sodium also has troublesome chemical properties. While it is compatible and noncorrosive with stainless steel, it reacts explosively — burns rapidly and instantly on exposure to either air or water — and great care must be taken to insulate it from either of these materials.

At ordinary temperatures, the sodium becomes a solid, which also makes maintenance difficult and poses problems for reactor start-up. The sodium is slow to begin its essential circulation and cooling. A host of minor design problems, the need for new types of valves, pumps, etc. to handle this liquid metal, await solution.

In the discussion of thermal reactors, we commented on the stabilizing properties of the delayed neutrons. In the fast neutron breeders this feature is largely missing; only about 0.25 percent of the neutrons (as against 0.7 percent in U^{235} fission) are delayed in U^{233} or Pu^{239} fission. The control situation is, thus, much more delicate, for there are not as many delayed neutrons to use in correcting mistakes. The fast neutrons add to the problem. While slow neutrons create another generation of fission events in 10^{-4} seconds, fast neutrons create the next round in 10^{-8} seconds. This is faster than even most electronic devices can respond. The LMFBR will be a tricky beast.

Summary

We have described in this section the conversion of the nuclear potential energy of heavy elements into kinetic and then thermal energy by nuclear reactors. We have, for the most part, focused our attention on how they work.

As Source Book readers are surely aware, the emergence of these devices has drawn mixed reaction in the scientific community and from the public. The promise of abundant electricity is not an unmixed blessing. To some extent nuclear reactors represent a trade-off — the obvious disadvantages of coal as a fuel for dangers still largely unquantified. We have described some of the risks in Chapters 3 and 4 of Volume I.

It seems apparent, however, that the next decade will be dominated by reactor building. The nuclear genie is out of his bottle; we will now see how well he is trained.

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APPENDIX 7
Source Book Reviewers

Source Book Reviewers

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